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Final Report

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COMPOSITE ACCELERATOR GRID INVESTIGATION FOR CESIUM ELECTRON BOMBARDMENT ION THRUSTER

(28 May 1969 to 28 April 1971)

Contract No.: NAS5-21023

Prepared by

Electro-Optical Systems
Pasadena, California

for

Goddard Space Flight Center
Greenbelt, Maryland



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ABSTRACT

Composite accelerator electrodes offer potential improvements in ion microthruster performance particularly between specific impulses of 1800 and 3500 seconds. Various composite electrode configurations were investigated for application on cesium bombardment ion thrusters. Tests with cesium thrusters were concentrated on three types of electrodes: bonded metal-ceramic, glass-coated metal, and glass-coated ceramic bonded to metal. Techniques for brazing niobium to alumina were adapted to this effort. Design constraints due to anticipated launch vibrations were examined. Design and performance considerations are discussed along with operational test results.

SUMMARY

This is the final report for NASA Contract Number NAS5-21023, "Composite Accelerator Grid Investigation," supported by the Auxiliary Propulsion Branch of Goddard Space Flight Center. The technical officer was Mr. R. O. Bartlett. The program was directed toward investigating the applicability of composite accelerator electrodes to cesium electron bombardment ion thrusters.

Composite accelerator electrodes were found feasible for use with Cesium bombardment thrusters, however additional development is needed to extend the useful life of the electrodes.

The effort consisted of a study of designs and materials, development of fabrication techniques, testing, and analysis. The material combinations selected for operational testing were niobium brazed to alumina, alumina metalized with molybdenum. Corning code 1723 glass was also identified as an alkali resistant material, however, no fabrication technique was developed.

A parallel effort by T. M. Heslin and A. G. Eubanks of the Advanced Materials Branch at Goddard Space Flight Center, produced a bubble-free glass coating on molybdenum accelerator electrodes and on alumina insulators. Early glass coating processes which used Corning code 7052 glass were later modified for Corning code 1723 glass coatings. The glass coated accelerator electrodes developed by Goddard Space Flight Center were operationally tested at EOS.

Several operational tests, lasting up to 320 hours, helped identify modes of operation and degradation. The primary modes of degradation

were cracking of the insulator, both ceramic and glass, and coating of the insulator with conductive material. These problems were attacked and some interesting approaches have suggested themselves for the investigation. The most promising of these is an electrode formed by coating a molybdenum-manganese/alumina electrode with Corning 1723 glass.

KEY TO SYMBOLS

<u>Symbol</u>	<u>Interpretation</u>
A	Open area of entire accelerator electrode
C	Center-to-center spacing of apertures
D	Diameter of apertures
H	Insulator thickness
J	Conductor thickness
I_B	Beam current = $ I_+ - I_- $
I_B/A	Beam current density
$I_B/NV_G^{3/2}$	Perveance per aperture
$I_B/V_G^{3/2}$	Perveance
I_{SP}	Specific impulse
I_+	Positive HV supply current
I_-	Negative HV supply current, drain current
N	Number of electrode apertures
P	Vacuum chamber pressure
P_A	Arc power
R	Number of rows of apertures from center to edge including center row
S	Diameter of active area of electrode
T	Transparency (open area/total area)
T_A	Accelerator electrode temperature
T_V	Vaporizer temperature
V_G	Screen to accelerator gap voltage
V_+	Discharge chamber voltage, positive high voltage
V_-	Accelerator voltage, negative high voltage
W	Web thickness (C - D)
η_M	Mass efficiency

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SECTION 1

INTRODUCTION

Near term satellite missions will require propulsion system specific impulses in the range of 1800 to 3500 seconds. For cesium electron-bombardment ion thrusters, these specific impulses correspond to acceleration voltages from 200 to 800 volts. Efficient ion accelerating electrodes require corresponding aperture diameters from 0.030 to 0.076 inch. A corresponding insulating gap from 0.010 to 0.038 inch must be maintained between the high voltage plasma and the accelerator electrode. Problems including aperture alignment and warpage make the use of large conventional two grid systems difficult, even when the electrodes are segmented and have spacers. As the apertures become small the corresponding plasma-to-accelerator gap also becomes small. On a conventional two electrode system this gap must contain the screen electrode. This means that in order to maintain electrical isolation, as the hole diameter gets small, the screen electrode must approach zero thickness and therefore is mechanically unstable. Composite accelerator electrodes replace the vacuum gap with an insulator and use the plasma sheath itself as the screen electrode. This insures alignment of the apertures and the structural stability of the gap.

The research effort to develop a composite accelerator suitable for use with cesium thrusters was initially directed toward identifying materials which are compatible with the hot cesium plasma for long periods of time. The second step was to develop techniques for fabricating electrodes using acceptable materials. The third step was testing. Comparing composite electrode operational test results with those of conventional electrodes pointed to new aperture

configurations and operating parameters. Electrodes developed by T. Helsin and A. Eubanks, NASA Goddard Space Flight Center, were also tested.

Section 2 of this report discusses the design considerations and Section 3 briefly discusses test equipment. Electrode fabrication is covered in Section 4. Section 5 gives test results and Section 6 contains the conclusions drawn from the effort.

SECTION 2

DESIGN CONSIDERATIONS

A number of questions regarding electrode design, electrode fabrication, and thruster operating parameters had to be defined before proceeding. The design parameters considered included hole array design, thermal stress, resistance and minimum conductor thickness, launch vibration stress, and perveance.

Since no theory exists on the behavior of composite ion extraction systems, the electrode design procedure was a progression based on past experience with the design parameters. The performance of small conventional two grid electrodes was taken as the basis for the design of composite electrodes. Some design considerations applicable to composite grids are discussed briefly here.

2.1 APERTURE ARRAY

The following equations relate the aperture size, spacing, and number of holes to the transparency of a hexagonal array.

$$N = 3R(R-1) + 1 \quad (1)$$

$$S = C(2R-1) \quad (2)$$

$$S = C \sqrt{1 + \frac{4}{3}(N-1)} \quad (3)$$

$$T = \frac{\pi}{2\sqrt{3}} \left(\frac{D}{C}\right)^2 \approx 0.907 \left(\frac{D}{C}\right)^2 \quad (4)$$

Equation (1) shows that the number of holes in a complete hexagonal array is 1, 7, 19, 37, 61, 91, 127, 169, 217, 271, 331, etc. Equations (2) and (3) are used to determine the area taken by the overall array. Equation (4) shows that for $0.074 < (D/C) < 0.91$ the transparency will be from 50 to 75 percent. This is the range of interest since discharge chamber power losses become too large for transparencies below 50 percent and structural integrity is lost above 75 percent.

2.2 THERMAL CONSIDERATIONS

The thermal coefficient of expansion is an important factor in selecting insulator-conductor pairs which are compatible for accelerator electrode fabrication and operation. The insulating materials selected were AL995 alumina (99.5 percent) pure Al_2O_3 , Lucalox (99.9 percent pure Al_2O_3), Corning code 7052 glass, and Corning code 1723 glass (alkali resistant). The conductor material used with AL995 and Lucalox was niobium (columbium) since their coefficients of thermal expansion are an extremely close match to the $1500^{\circ}C$ temperature reached during fabrication. Molybdenum-manganese was also used successfully with AL995. Since the coating is only 0.001 to 0.004 thick, differences in thermal expansion were not a problem.

Kovar was found to be a good match for both glasses at low temperatures, however, it was not suitable at the $1450^{\circ}C$ glass coating temperatures. Molybdenum was the final selection for the conductor to be glass coated. Molybdenum has a coefficient of thermal expansion slightly higher than glass. During fabrication, the glass solidifies and the molybdenum contracts more than the glass during cooling. This places the glass in compression at room temperature and at the 100 to $200^{\circ}C$ operating temperature.

2.3 ELECTRICAL RESISTANCE OF THE CONDUCTOR

The acceptable electrical resistance of the conductor can be a design constraint for very thin conductors such as molybdenum-manganese. A minimum thickness approximation was calculated assuming a 5-inch diameter electrode with all the current flowing to the center aperture through 75 percent transparent stainless steel as a worst case. The minimum conductor thickness was found to be 0.0001-inch for 1 ohm of resistance. This is significantly thinner than all conductors under consideration.

2.4 LAUNCH VIBRATION STRENGTH

In order to develop design parameters for flight electrodes, mechanical strengths were calculated for 1-inch and 5-inch diameter composite electrodes. One-inch was a convenient laboratory size and 5-inches would be suitable for a 1 to 2 mlb MESC-type flight thruster. The material combinations considered were Lucalox-niobium, Lucalox-aluminum, Corning 1723 glass-molybdenum, and Corning 1723 glass-Kovar. The insulator thickness (and aperture radii) vary continuously from 0.010 to 0.080-inch. Conductors 0.001 and 0.020-inch thick were considered. The 1969 Application Technology Satellite launch environment specifications are used as representative design stresses. The launch vibration considered is given in Table I.

TABLE I
ATS SINUSOIDAL LAUNCH VIBRATION SPECIFICATION

Frequency	Sweep	Load Factor Amplitude
5-22	2 octaves/minute	0.5 inch double amplitude
22-200	2 octaves/minute	12 g (o-peak)
200-2000	2 octaves/minute	5 g (o-peak)

The calculations were made by a computer in stages. The first calculation determined the neutral frequency as a function of electrode transparency. This was done for each material combination, conductor thickness, and insulator thickness. A hexagonal hole array was assumed throughout. The worst case loading will occur when the resonant frequency falls within vibration requirements of Table I. If resonance occurs, the gain (Q) was assumed to increase from 1.0 to 25. This means that at resonance the stresses will increase by a similar amount. Vibration at resonance is therefore the most likely failure mode. Failure will occur if the calculated stress exceeds the yield strengths of the materials. In designing electrodes, the calculated stresses will not exceed one-half the yield strengths of the materials. Representative yield strengths are:

- a. Lucalox - 20,000 psi
- b. Niobium - 40,000 psi
- c. Corning Code 1723 Glass - 40,000 psi
- d. Molybdenum - 95,000 psi

The calculations indicated that all flat 1-inch diameter composite electrodes and dished 5-inch diameter composite electrodes are strong enough. The natural frequencies were all above 2000 Hz and therefore resonance and associated gains were avoided during sinusoidal vibration. The dished electrodes were assumed to have a 12-inch radius of curvature since to be considered as dished, an electrode was taken to be a 10 degree or larger segment of a sphere.

Launch environment stress can be met by 5-inch diameter flat electrodes if they are designed within specific thickness, aperture diameter, and transparency limitations. These design limitations have been determined for the two material pairs most likely to be used for flight composite accelerator electrodes. These are niobium

brazed to Lucalox (99.9 percent pure Al_2O_3) and Corning Code 1723 glass coated molybdenum. If the insulator thickness is 0.020-inch or thicker and the conductors are 0.001 or 0.020-inch, then the highest allowable design transparency is 80 percent. At a transparency of 60 percent, all material pairs examined for 5-inch flat composite electrodes could withstand launch vibration.

The conclusion of this study is that 5-inch diameter composite electrodes can be designed sufficiently strong to withstand a launch vibration environment. This result implies that high strength dished composite electrodes are not necessarily required to meet launch vibration as previously anticipated.

2.5 PERVEANCE

The perveance equation relates the desired accelerating potential with aperture diameter, gap, and beam current. To achieve optimum operation, it has been shown experimentally that the aperture diameter should be approximately twice the gap. This essentially fixes the accelerating voltage, aperture diameter, and gap of a given specific impulse for an assumed perveance.

$$P = \frac{I_B}{V_+^{3/2}} \propto \frac{A_1}{G^2}$$

where

- P = Perveance
- A_1 = Area of an aperture
- G = Gap distance for high voltage
- I_B = Beam current
- V_+ = Positive high voltage

Using the screen-accelerator electrodes on the DG cesium ion thruster¹ as typical, perveance was calculated to be 2.2 nanopervs/aperture with a beam current density of 3 mA/cm^2 of open area. Assuming a mass efficiency of 100 percent, specific impulses from 1800 to 3500 seconds correspond to voltages from 250 volts to 800 volts. This corresponds to aperture diameters from 0.025 to 0.060-inch. Slightly larger apertures were used in early composite electrodes for ease of fabrication.

Composite accelerator electrodes were found to be capable of higher current density and higher perveance operation than conventional electrodes used on the DG thruster. Data delineating composite accelerator operation will be given in Section 5.

SECTION 3

TEST EQUIPMENT

The test equipment consists of the thruster, instrumentation, power supplies, and vacuum system.

A DG cesium electron bombardment ion thruster was used for most electrode testing. Numerous reports are available which describe the DG thrusters performance with full size electrodes.¹

The first feed system used for composite grid tests was a simple boiler. This was quickly found impractical and uncontrollable. A 5-pound zero-g type feed system with pressure relief valve, manual vapor valve and a 0.50-inch diameter wick replaced the boiler feed system. This system gave much better control and allowed reusing the feed system without extensive work after each test. Some of the problems experienced with the second feed system included periodic sticking of the pressure relief valve, slow response time of the vaporizer, contamination of the wick by air leaking past valves, and occasional expelling of cesium into the arc chamber.

Slow vaporizer response time was remedied by incorporating a 0.25-inch diameter vaporizer which operated at a higher temperature. This new vaporizer also seemed to have reduced expelling problems. Air still diffused slowly through valves, when the system was stored in air, however, the resulting contamination problems were reduced by storing the system in dry nitrogen.

The thruster was first modified to accept test electrodes by adding a dummy screen electrode with a 1.0-inch diameter hole in the center. Three mounting clamps held the composite electrodes in place during operation. The contact patch of each mounting clamp on the electrode was minimized to prevent non-uniform heat conduction and possible thermal stress in the electrode. The second electrode mounting clamp was a symmetrical stainless steel ring and shadow shields. This provided a uniform positive contact on the electrode and shielded the thruster body from downstream electrons. The second mounting configuration was used for the majority of the tests. The final mounting was designed to hold flanged composite electrodes in a possible flight type configuration. A flange on the upstream side of the electrode insulator is rigidly clamped to the mounting screen by a ring of machine screws. This mounting configuration was designed to eliminate any mechanical or thermal stress caused by mounting the electrode.

The power conditioning used for all testing on the 5-inch thruster was the same as that used to operate other DG thrusters. It included positive high voltage, negative high voltage arc, magnet, cathode, manual feed valve, vaporizer, pressure relief valve, reservoir, and neutralizer power supplies. The vacuum system controls, neutral cesium detector power supplies and meter, and two dual channel strip chart recorders were located near the power conditioning. Thermocouple meters monitored the temperatures on the accelerator, cathode, manual feed valve, vaporizer, and reservoir.

An automatic control system controlled the beam current. This was done by sensing the beam current, comparing it with a manual reference, and using the difference to adjust the vaporizer power. The control system available had been previously used to control DG thrusters at much higher beam levels and was insensitive to the low beam currents

used on this program. To help compensate for the insensitivity, the current sensor and amplifier gains were increased.

The problem of the insensitivity of the beam current control system eventually led to the change to a 1.0-inch diameter thruster² and its associated feed and control systems. This small thruster simplified the control problem, but introduced non-uniform plasma problems which had been avoided by using the 5.0-inch thruster.

The tests were all performed in a 2 by 6 foot vacuum chamber. Two parallel mechanical pumps and two diffusion pumps with liquid nitrogen cooled baffles were used.

SECTION 4

ELECTRODE FABRICATION

The research program to develop composite accelerator electrodes consisted of materials selection, development of fabrication techniques, and configuration development.

First, insulator materials suitable for standing off high voltages in hot cesium plasma were identified and tested. Candidate insulators included alumina, boron nitride, fused quartz, Corning code 7052 glass, Corning code 1723 glass, and berylia. Alumina, in the form of 99.5 percent pure AL995 and 99.9 percent pure Lucalox, is commonly used as an insulator in cesium ion thrusters and was not tested. Pyrolytic boron nitride was unacceptable for flight electrodes because of its lack of strength, however, it was acceptable for laboratory use. Fused quartz, 7052 glass, and 1723 glass were tested in a worst-possible-case experiment for compatibility with 300°C cesium vapor for 18.5 hours. Extrapolating the weight losses, an electrode made of 1723 glass would have a mass loss of 0.86 percent during a 1000 hour operation. This worst-case is certainly acceptable for laboratory work and possibly for flight electrodes. The 7052 glass had six times the mass loss of the 1723 glass. The fused quartz was acceptable before machining, however, if holes were drilled or beveled after fusing, the surface was attacked by cesium vapor.

Processes for connecting a conductor to the selected insulators were then investigated. The conductor which most nearly matched the coefficient of thermal expansion of alumina is niobium (columbium). An EOS proprietary braze process was used to bond 0.020-inch niobium

sheet to a 0.037-inch thick alumina disc. This process was the basis of the brazed electrode fabrication technique discussed later. An attempt was made to plasma spray molybdenum frit onto alumina, but adhesion was poor and the process was abandoned. A similar alumina plasma spraying technique was attempted on molybdenum and niobium substrates also with poor adhesion. A thin molybdenum-manganese metalizing layer was applied to alumina with good adhesion. Electrodes fabricated using the moly manganese process are discussed later. Attempts to metalize the pyrolytic boron nitride with palladium resulted in weak bonds. It is felt this technique could have been satisfactorily developed with the proper testing program. Pyrolytic boron nitride insulators are only suitable for electrode configuration testing in the laboratory and therefore this process was abandoned. Attempts at ion plating aluminum on alumina yielded poor bonds and was also abandoned for lack of development time.

No attempts to coat glass on a substrate were conducted on this program since similar work was underway at NASA Goddard. A summary of the techniques for producing bubble-free glass coatings on molybdenum substrates as developed by T. M. Heslin and A. G. Eubanks of Goddard Space Flight Center is reported in GSFC X-735-70-204, April 1970.

A technique for applying a coating of Corning code 1723 glass to alumina was also developed at NASA Goddard. Electrodes produced by this technique were not tested at this writing.

The last step in developing techniques for fabricating composite electrodes was to devise electrode configurations, test them, and systematically modify the format to produce the desired electrodes. A list of all of the electrodes fabricated and/or tested at EOS is given in Table II. The development of the fabrication procedure is delineated for brazed alumina electrodes and moly manganese metalized alumina electrodes.

TABLE II
COMPOSITE ACCELERATOR ELECTRODES FABRICATED AT EOS

Electrode No.	Insulator		Conductor		Hole Diameter	Center-to-Center Spacing	No. of Holes	Comments
	Thickness (inch)	Material	Thickness (inch)	Material				
1	0.037	AL995	0.020	Nb	0.076	0.100 (inch)	61	Broke during drilling due to faulty clamp. Solid Nb, perforated braze.
2	0.037	AL995	0.020	Nb	0.076	0.100	61	Solid Nb, solid braze. Braze pulled from webs. Tested.
3	0.038	AL995	0.020	Nb	0.076	0.100	61	Solid Nb, perforated braze. Broke during drilling. Sectional no stress relieving found.
4	0.038	AL995	0.020	Nb	0.076	0.100	61	Solid Nb, perforated braze. Pin in place during brazing. Braze wicked up into holes and some webs unbrazed.
5	0.038	AL995	0.005	Nb	0.076	0.100	61	Solid Nb, perforated braze. Heated to 300°C for 30 min. to relieve stresses if any. Tested.
6	0.037	AL995	0.005	Nb	0.076	0.100	61	Solid Nb, perforated braze. Thermal stress relieved also.
7	0.037	AL995	0.005	Nb	0.076	0.090	61	Broken drilling pins.
8	0.037	AL995	0.005	Nb	0.076	0.090	61	Cracked during brazing.
9	0.036	AL995	0.005	Nb	0.072	0.091	61	

TABLE II

COMPOSITE ACCELERATOR ELECTRODES FABRICATED AT EOS (contd)

Electrode No.	Insulator		Conductor		Hole Diameter	Center-to-Center Spacing (inch)	No. of Holes	Comments
	Thickness (inch)	Material	Thickness (inch)	Material				
10	0.036	AL995	0.005	Nb	0.0715	0.091	61	Cracked during operation Tested.
11	0.036	AL995	0.005	Nb	0.076	0.090	61	Cracked during test.
12	0.023	AL995	0.005	Nb	0.0435	0.060	127	Poor braze.
13	0.023	AL995	0.005	Nb	0.0435	0.060	127	Good
14	0.023	AL995	0.005	Nb	0.0435	0.060	127	Good
15	0.036	AL995	0.001	MoMn	0.070	0.090	61	Good - cracked during test.
16	0.036	Lucalox	0.005	Nb	0.076	0.100	61	Tested - cracked during test.
17	0.020	AL995	0.005	Nb	0.076	0.100	61	AL995 beveled 0.012 inch, lost in brazing.
18	0.020	AL995	0.005	Nb	0.076	0.100	61	AL995 beveled 0.012 inch, broken in storage.
19	0.036	Lucalox	0.005	Nb	0.076	0.100	61	Good - new
20	0.036	AL995	0.005	Nb	0.076	0.100	61	Flanged - broken during brazing.
21	0.036	AL995	0.005	Nb	0.076	0.100	61	Flanged - broken during brazing.
22	0.036	AL995	0.005	Nb	0.076	0.100	61	Flanged - broken during brazing.
23	0.036	AL995	0.005	Nb	0.076	0.100	61	Flanged - broken during brazing.

TABLE II
COMPOSITE ACCELERATOR ELECTRODES FABRICATED AT EOS (contd)

Electrode No.	Insulator		Conductor		Hole Diameter	Center-to-Center Spacing	No. of Holes	Comments
	Thickness (<u>inch</u>)	Material	Thickness (<u>inch</u>)	Material				
24	0.036	AL995	0.005	Nb	0.076	0.100	61	Flanged. Tested.
25	0.036	Lucalox	0.005	Nb	0.076	0.100	61	Flanged. Tested.
28	0.037	AL995	0.001	MoMn	0.076	0.100	61	Broken during cleaning after operation.
	0.002		0.004	Ni				
29	0.027	AL995	0.001	MoMn	0.043	0.060	127	(GSFC 1) cracked during glassing.
	0.002	1723 Glass	0.001	Ag				
30	0.027	AL995	0.002	MoMn	0.043	0.060	127	(GSFC 2) cracked during glassing.
	0.003	1723 Glass						
31	0.037	AL995	0.005	Nb	0.076	0.100	61	(GSFC 3) (Was No. 6) Cracked during glassing.
	0.002	1723 Glass						Tested.
32	0.023	AL995	0.002	MoMn	0.043	0.060	127	To GSFC 2/71 for glassing, returned 4/71.
33	0.002	1723 Glass						
	0.026	AL 995	0.002	MoMn	0.076	0.100	61	To GSFC 3/71 for glassing, returned 4/71.
34	0.002	1723 Glass						
	0.026	AL995	0.002	MoMn	0.076	0.100	61	To GSFC 3/71 for glassing.
35	0.026	AL995	0.002	MoMn	0.076	0.100	61	To GSFC 3/71 for glassing.
			Both sides					Tested
36	0.035	AL995	0.003	MoMn	0.076	0.100	91	Cracked during metallizing. To GSFC 3/71.
37	0.035	AL995	0.003	MoMn	0.076	0.100	91	To GSFC 3/71.

4.1 BRAZED ALUMINA ELECTRODES

The first attempts at vacuum niobium to alumina using the EOS proprietary braze technique was performed on non-perforated discs. Adjustments in surface flatness and the amount of weight on the brazing fixture gave an excellent ternary bond.

The alumina insulators then had to be perforated with the appropriate hole matrix. Two methods exist for perforating the alumina discs. The holes can be ground using diamond tools. An ultrasonic drill, such as the UMT-3 Rotary Ultrasonic Machine tool by Branson Sonic Power, greatly reduces the perforating time and produces diameter and position tolerances of ± 0.001 inch. An alternate method is to drill the holes in unfired alumina and then fire the disc. This alternate method produces shrinkage which, after compensation, gives tolerances of ± 0.002 inch. The first method is approximately three times as expensive as the alternate.

Niobium was selected as the electrode conductor material because its coefficient of thermal expansion is an excellent match with alumina.

A series of tests were run to determine whether the niobium and/or braze should be drilled before or after brazing. Several electrodes were lost during brazing due to braze filling around pins used to locate the perforated niobium and/or braze. After brazing, the braze material is very hard and the niobium is soft. This makes machining brazed electrodes difficult. The final procedure uses perforated braze washers and non-perforated niobium. This reduces the amount of hard braze in the holes which must be drilled after brazing and minimizes hole alignment problems.

Testing the composite electrodes indicated that beveling the downstream side of the niobium was necessary for minimizing drain currents. This eliminates the accelerator electrode material which directly intercepts a well focused ion beam.

The machining process can be summarized as follows:

- a. Drill holes in the braze and niobium using the holes in the alumina as guides. Drills are high speed steel or carbide. Alcohol is used as a lubricant. The electrode must be backed with wood or fiberboard. Holes are drilled 5 percent under size to avoid breaking the alumina.
- b. Bevel the niobium with a 90° carbide countersink using toothpaste and water as a lubricant. Use a low speed drill in fixed position and raise the backed electrode to the drill.
- c. Hone the electrode with 27μ alumina powder with 60 to 80 psi air pressure. Hone in the holes from the alumina side (upstream) only.
- d. Operate the composite electrode on the thruster for a few hours. It is suspected that the ion beam, cesium plasma, and heat change the properties of the braze material making it easier to do the final machining.
- e. Bevel the niobium with a 12 flute ball reamer about twice the diameter of the holes.
- f. Hone the electrode from the upstream side.
- g. Wash with acetone, alcohol, distilled water, and then dry it in a vacuum oven.

The final brazed alumina electrode configuration was developed for several reasons. First, there was a fairly high probability that some alumina insulators were being damaged during mounting on the thruster. Second, the clamping method being used provided rigid support by a stainless steel mounting screen. When heated, this mounting screen could apply force to the clamped composite electrode either by differential coefficient of thermal expansion or by warpage. Third, axial and radial thermal gradients could be produced by the large radiating mounting clamp.

To eliminate these problems a mounting flange was brazed to the perimeter of the upstream side of the electrode insulator. A convolution helped absorb stresses from the mounting screen. A large radiating clamp was not necessary so thermal gradients were minimized. Operational tests have demonstrated the effectiveness of this mounting flange. It is presently thought that a flight composite accelerator electrode would have a similar mounting flange.

4.2 MOLYBDENUM-MANGANESE METALIZED ALUMINA ELECTRODES

Moly-manganese metalizing is a process commonly used for coating ceramics with metal which can be connected to other metals to form vacuum tight seals. The alumina insulators used were AL995 (99.5 percent pure) and Lucalox (99.9 percent pure). The moly-manganese can be applied by painting it on in solution or by applying molybdenum-manganese tape. The coated electrode is dried and then fired at 1625°C in a forming-gas atmosphere. This high temperature removes all tape remnants and binders which are applied with the moly-manganese. The resulting conductive coating is approximately 0.0005-inch thick. The first moly-manganese metalized alumina electrode was nickel plated to a thickness of 0.005-inch for added strength. During testing, the metalizing lifted off the alumina insulator. This is attributed to the stress induced by the difference in the coefficients of thermal expansion. Subsequent electrodes eliminated the nickel plating and no further adhesion problems were encountered.

Operational tests also indicated that care must be taken to avoid moly-manganese inside the holes. On operational electrodes, the downstream side of the holes were lightly beveled using a diamond tool with alcohol lubricant.

The final version of the moly-manganese metalized alumina electrodes was sent to Goddard Space Flight Center where a coating of 1723 glass was applied to the alumina. This coating improved the optics of the grid, covered the relatively porous alumina with non-porous glass, and provided a medium by which a mounting flange and shadow shield could be attached to the basic composite electrode. Figure 1 shows such a grid fabricated at Goddard Space Flight Center.

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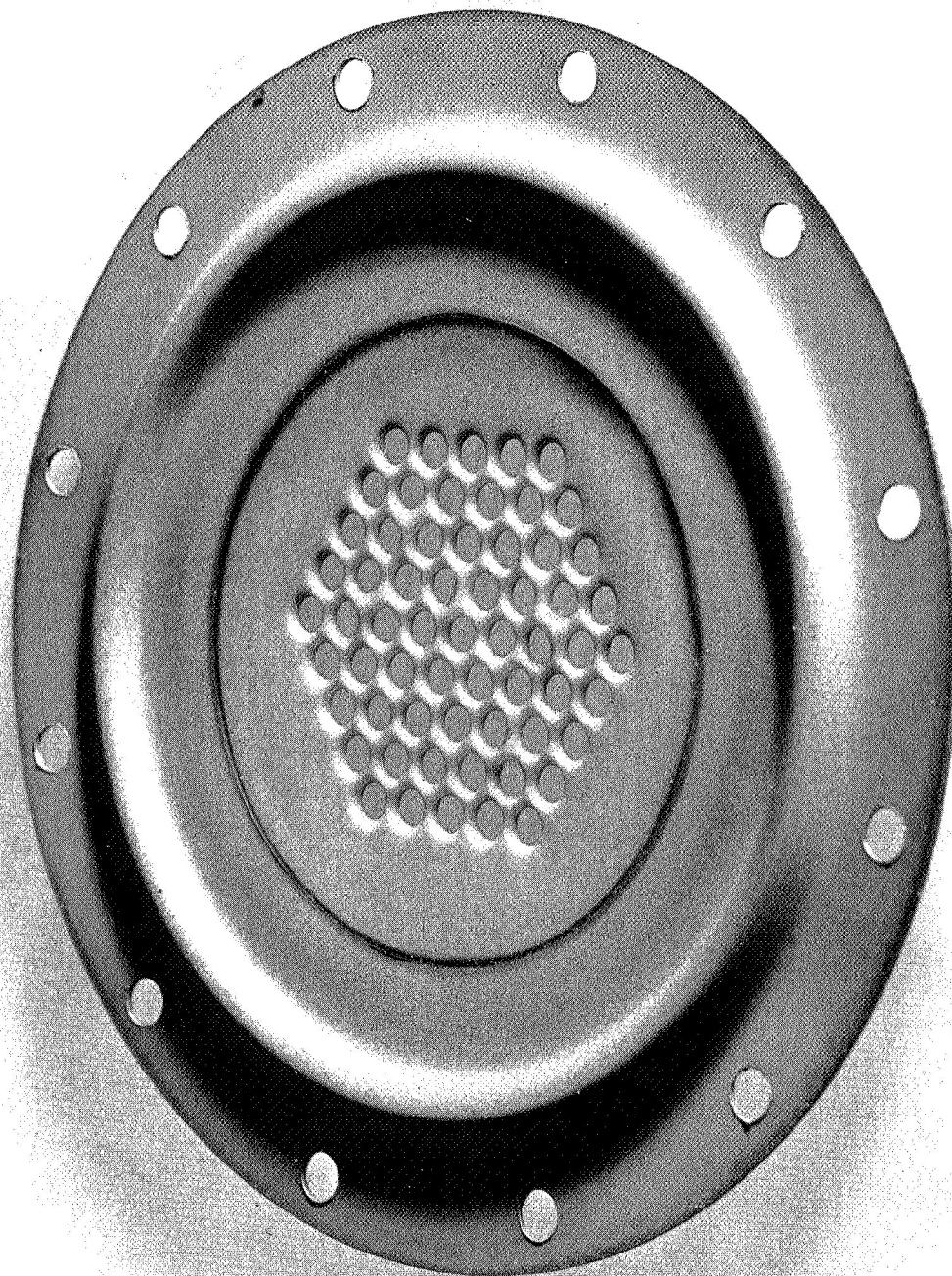


Figure 1. 1723 Glass Aluminum and Moly-Manganese Electrode No. 33 (Upstream)

SECTION 5

TESTING

A test sequence was derived to start operational testing with known electrodes on the familiar DG thruster. Composite accelerator electrodes are ultimately planned to be used on the advanced MESC (magneto-electrostatic containment) thruster. The relatively uniform plasma near the axis of the DG discharge chamber was used to simulate the uniformly distributed plasma of the MESC thruster. This was done successfully using a conventional screen and accelerator electrodes with a uniform hole pattern (type 1). The next step was to test various composite accelerator electrodes using the same uniform hole pattern as on the conventional two grid system. The aperture diameter, transparency, specific impulse and beam current were then to be modified in a logical progression as shown in Table III.

TABLE III

TEST PLAN

Type No.	D (in.)	C (in.)	W (in.)	T (%)	H (in.)	V+ (kV)	I _{sp} (sec.)	No. Holes	S (in.)
1	0.076	0.100	0.024	52.3	0.020	1150	3860	61	0.900
2	0.076	0.091	0.015	63.3	0.020	1150	3860	61	0.773
3	0.0465	0.0615	0.015	51.9	0.010	595	2780	127	0.799
4	0.0465	0.0565	0.010	61.4	0.010	595	2780	127	0.735
5	0.031	0.041	0.010	51.7	0.005	342	2100	271	0.778
6	0.031	0.035	0.004	71.0	0.005	342	2100	331	0.735

Electrode type Nos. 1, 2, and 3 were fabricated and operationally tested. Several undefined characteristics of composite electrode fabrication,

operation, focusing, and ageing made the testing of more advanced type number of electrodes premature. The composite electrodes operated well with voltages (V_+) and corresponding specific impulses far below those anticipated in Table III. The program goal was to operate an advanced composite accelerator electrode for 1000 hours. This goal was not achieved although some promising configurations were developed near the end of the program.

A chronological summary of all testing done on this program at EOS is given in Table IV. Unless otherwise indicated, electrodes had a 61-hole pattern, approximately one inch in diameter. The seven tests which were run for over 100 hours are reported further and compared to the conventional screen-accelerator electrode operation which was run as a baseline.

5.1 TEST THRUSTER WITH CONVENTIONAL ELECTRODES

The DG cesium electron bombardment thruster with dummy screen electrode was installed in a 2- by 6-foot vacuum chamber. Standard screen and accelerator electrodes with an alumina spacing washer between them were installed on the thruster. The accelerator electrode had 61 holes of 0.076-inch diameter with a center-to-center spacing of 0.100-inch (type 1) and was identical to the conductor of the first composite electrodes tested. The gap was equal to the insulator thickness of the first composite electrode. The screen had countersunk holes slightly larger than the accelerator holes. These were designed to approximate the operation of the first composite electrodes and serve as a baseline for data.

A simple boiler feed system was used for the first run. The run was characterized by expelling of cesium into the arc chamber and a lack of feed control. A 5-pound reservoir with a manual valve, pressure

TABLE IV

TESTING SUMMARY

Start Date	Electrode Type	Electrode No.	Operating Hours	I _B	V ₊	Comments
22 Aug 69	Conventional 2 Grids	-	0.4	4 to 9	1000	Feed problems.
25 Aug 69	Conventional 2 Grids	-	7	12 to 20	1000	Control problems.
28 Aug 69	Conventional 2 Grids	-	5.75	6 to 14	310 to 920	Preliminary mapping.
12 Sep 69	Conventional 2 Grids	-	3.25	7 to 11	900	Vaporizer not controllable.
17 Sep 69	Conventional 2 Grids	-	24	8 to 19	310 to 920	Performance mapping.
22 Sep 69	Brazed AL995	2	0.5	7	350 to 450	Anode short.
30 Sep 69	Brazed AL995	5	3.75	4.5 to 9.3	140 to 300	High drains from coating. Electrode hold down clamp modified.
24 Oct 69	Brazed AL995	5	0.9	3 to 11	315	Anode short.
4 Nov 69	Brazed AL995	6	1.3	3	500	Same as 5.
5 Nov 69	7052 Glass	43				Indium seal melted and shorted.
6 Nov 69	7052 Glass	39	0.3	1 to 3	250	1.5 in. dia. mounting flange attached with glass.
12 Nov 69	7052 Glass	39	1.25	3 to 5	340	2 x 10 ⁻⁴ torr of argon showed relatively well focused beam when drains were low.
17 Nov 69	Conventional 2 Grids		3	4 to 8	300 to 500	Argon showed almost parallel beam.
19 Nov 69	7052 Glass	37	0.5	6 to 13	350	100° bevel upstream.
26 Nov 69	MoMn - AL995 with Ni plating	A	1.0	7.4 to 13	300 to 520	MoMn in holes and on outside edge of insulator.

TABLE IV
TESTING SUMMARY (contd)

Start Date	Electrode Type	Electrode No.	Operating Hours	I _B	V ₊	Comments
3 Dec 69	MoMn - AL995 with Ni plating	A	0.9	7.8	320 to 500	No arcing for 0.8 hours. Conductor pulled from AL995. Cracked during cleaning.
5 Jan 70	Brazed AL995	10	1.3	8 to 11	330 to 610	Very smooth operation with low drains.
12 Jan 70	Brazed AL995	11	1.4	10.5	600	Same as 10. Neutralizer tried after startup. No effect on performance.
13 Jan 70	Brazed AL995	10	150*	8	500 to 600	Beveled Nb downstream. Preheated and neutralized during startup.
29 Jan 70	7052 Glass	64	1.0	2 to 7	460	Copper gasket. Glass breakdown on edge hole webs.
10 Feb 70	Brazed AL995 127 holes-beveled	13	7.4	11.3	200 to 690	Argon showed full beam 35° wide.
23 Feb 70	Braxed Lucalox	16	3.5	5 to 12	350 to 500	High resistive drains.
25 Feb 70	Brazed Lucalox	16	1.3	8 to 11	500	Stopped to change control loop gains.
26 Feb 70	Brazed Lucalox	16	0.5	5	460	Control better.
4 Mar 70	Brazed AL995	10	200*	8	400 to 500	Preheated accel., neutralized beam, terminated by insulated cracks.

* Further analysis of these long tests follows.

TABLE IV
TESTING SUMMARY (contd)

Start Date	Electrode Type	Electrode No.	Operating Hours	I _B	V ₊	Comments
19 Mar 70	Thick 7052 glass		264*	8	420	Preheated accel. Neutralized during part of run. Web missing.
10 Apr 70	Thick 1723 glass		3.5	5	445	Glass breakdown on outside of edge holes due to thin glass.
14 Apr 70	MoMn on AL995	15	1	4 to 7	515	Unstable control system vap should control from I ₊ not I _B .
15 Apr 70	MoMn on AL995	15	56	8.4	490	Resistive drains.
28 Apr 70	MoMn on AL995	15m	212*	6.2	850 to 950	Countersink both sides. Low perveance.
15 May 70	MoMn on AL995	15 mm	5.2	2	900	Stopped to inspect for cracks--none.
18 May 70	MoMn on AL995	15 mm	66	5.5	925	Power failure at 40 hr. Terminated by insulator cracks.
27 May 70	Flanged AL995	24	7	7 to 9	530	Operated well. Stopped to prepare No. 25.
2 Jun 70	Flanged Lucalox	25	9	8 to 9	530	Perimeter braze droplet shorted V ₊ TO V ₋ . Easily cleaned.
4 Jun 70	Flanged Lucalox	25	104*	9 to 14	525	Resistive coating in apertures of insulator. Possibly over driven.

* Further analysis of these long tests follows.

TABLE IV
TESTING SUMMARY (contd)

Start Date	Electrode Type	Electrode No.	Operating Hours	I _B	V ₊	Comments
10 Jun 70	Flanged 7052 glass	-	320*	6	515	Boundary holes sealed with Ceramabond.
8 Sep 70	Flanged Lucalox	25	2.0	6.0	500	1 inch thruster checkout.
10 Sep 70	Flanged Lucalox	25	6.4	6.8	480	1 inch thruster checkout.
25 Sep 70	Flanged Lucalox	25	5.25	5.9	505	1 inch thruster checkout.
28 Sep 70	Flanged Lucalox	25	46.5	6.2	505	End checkout 1 inch thruster.
15 Oct 70	Glassed AL995/Nb 127 holes, flanged	26	73.0	6.0	500	Cracked before starting.
29 Oct 70	Flanged Lucalox	25	6.5	3.6	440	Define startup procedure.
30 Oct 70	Flanged Lucalox	25	1.25	3.7	440	Define startup procedure.
2 Nov 70	Flanged Lucalox	25	2.67	7.8	525	Define startup procedure.
8 Dec 70	Flanged Lucalox	25	6.0	1.4	500	Practice startup.
10 Dec 70	Flanged Lucalox	25	3.2	8.2	500	Define operational control decisions.
11 Dec 70	Flanged Lucalox	25	4.0	5.4	500	Define operational control decisions.
14 Dec 70	Flanged Lucalox	25	5.4	5.3	500	Define operational control decisions.
21 Dec 70	Glassed AL995/ 127 holes, flanged	29	2.2	5.8	300	Perfect startup, crack-electrical breakdown.

* Further analysis of these long tests follows.

TABLE IV
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 TESTING SUMMARY (contd)

Start Date	Electrode Type	Electrode No.	Operating Hours	I _B	V ₊	Comments
1 Feb 71	Glassed AL995/Nb 61 holes, flanged, shadow shield	30	165.0*	5.7	500	High percentage drains due to crack propagation.
16 Mar 71	MoMn both sides of AL995, flanged, shadow shield.	35	26	5.3	600	Good thruster control
31 Mar 71	MoMn both sides of AL995, flanged, shadow shield.	35	1.7	8.7	650	Mapped beamsread

* Further analysis of these long tests follows.

TABLE V

CONVENTIONAL ELECTRODE OPERATIONAL DATA

Selected Operational Data Points for Conventional 1.5 inch
Diameter Electrodes on a DF Cesium Electron Bombardment Thruster

Data Point No.	57	78	75	82	47	51	65	72
V_+ (V)	310	330	500	510	700	710	905	900
V_- (V)	970	275	250	810	490	517	475	20
I_- (mA)	0.46	0.35	0.49	0.70	2.2	0.58	1.4	0.22
I_B (mA)	14.64	5.65	8.31	14.8	15.3	12.72	17.8	9.48
* I_{SP} (Sec.)	2180	2240	2760	2780	3250	3290	3700	3700
I_-/I_B (%)	3.1	6.2	5.9	4.7	14.4	4.6	7.9	2.3
$I_B/NV_G^{3/2} \left(\frac{\eta_{\text{pervs}}}{\text{hole}} \right)$	5.24	6.35	6.59	5.10	6.13	4.64	5.67	5.59
I_B/A (mA/cm ²)	8.18	3.16	4.64	8.27	8.55	7.12	9.96	5.30
T_A (°C)	223	178	182	220	250	214	260	208

* ($\eta_M = 100\%$)

relief valve, and vaporizer were substituted for the boiler feed system. Thermocouples were placed on the reservoir, vaporizer, manual valve, cathode, and accelerator electrode. During pumpdown of the vacuum chamber, the manual valve was closed and the pressure relief valve was open. When a pressure of 10^{-5} torr was reached, the manual valve was opened. The pressure relief valve was left open until the reservoir was heated to 100°C , and then it was closed.

The thruster was operated four times for 0.4, 7, 5.75, and 3.25 hours as shown in Table IV. Automatic controls were used to feed back beam current and regulate vaporizer temperature. During fifth operation of the thruster with conventional electrodes, the operational characteristics of the system were completely mapped. Data systematically taken during a 24-hour run is summarized for four specific impulse domains on Table V.

The perveance per aperture and percentage drains are the critical parameters. The perveance indicates how much high voltage is necessary to extract the desired beam. The percentage drains describe the effectiveness of the aperture configuration, indicate the focusing of the beam, and characterize the match between the arc chamber and accelerator grids. The perveance per aperture for conventional electrode operation varied from 4 to 6 nanopervs per aperture. The percentage drains varied from 2 to 4 percent

5.2 BRAZED ALUMINA ELECTRODE NO. 10 - 150 HOUR TEST

Electrode No. 10, consisting of 0.005-inch thick niobium brazed to 0.037-inch thick AL995, was installed on the DG cesium electron bombardment thruster for testing. The electrode had 61 unbeveled holes, 0.072 inch in diameter on 0.091-inch center-to-center spacing. The thruster was operated for 1 hour 18 minutes continuously; 32 minutes were with drain currents below 3 percent of the beam current. Numerous small arcs in the apertures accompanied higher drain currents near the end of the test.

Electrode No. 10 was removed from the thruster and inspected. The insulator in the holes was coated with a conductor which is thought to be a combination of a braze material and niobium. Careful examination revealed that the braze and niobium extended into the aperture so that the accelerator electrode could be directly bombarded by the cesium ion beam. It is believed that this direct impingement caused sputtering and evaporation of the conductor which plated out on the insulator in the apertures. This conductor in the holes could be evaporated or eroded by direct ion beam impingement if the deposition rate is low. Since the deposition rate was high, the conductor in the apertures could cause further defocusing which, in turn, causes an increase in the deposition rate. This eventually leads to surface breakdown and arcing. This theory was supported by a previous materials analysis and by operating composite electrode No. 11.

Electrode No. 10 was beveled on the downstream side with a 120° chamfer. This was accomplished with a carbide countersink. The electrode was preheated to 120°C before starting the thruster using the neutralizer filament. Thruster operation was greatly improved due to beveling the electrode and the preheating. The thruster was operated continuously for 150 hours.

The percentage drains are given as a function of time in Figure 2. After the first 30 hours of operation, the percentage drains increased steadily. Typical operating points are given in Table VI. Electrode No. 10 is shown in Figure 3 after 150 hours of operation. The two dots on the periphery of the insulator are chips from machining which did not produce insulator breakdown.

Many of the holes had the insulators partially coated. A similar coating found on the ground screen tests underwent spectrographic analysis. The major constituents were niobium and aluminum which could have come

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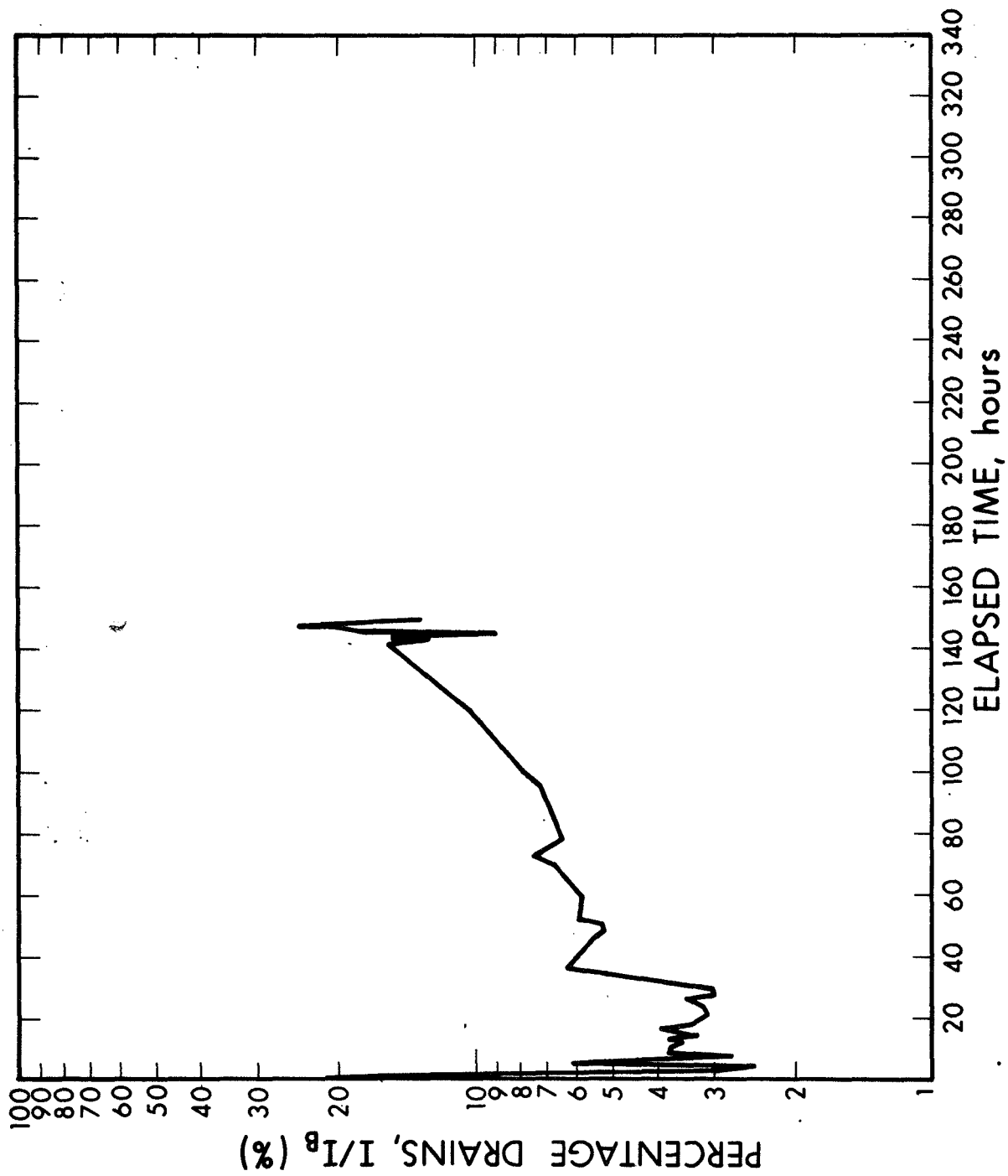


Figure 2. Percentage Drains Histogram for 150 Hour test

TABLE VI

TYPICAL OPERATIONAL DATA FOR BRAZED AL925 ELECTRODE NO. 10 - 150 HOUR TEST

Data Point No.	154	176	192	201	214	235
V_+ (V)	640	640	655	660	655	505
V_- (V)	102	140	132	134	101	72
I_B (mA)	8.49	10.14	11.76	8.74	9.02	9.0
I_- (mA)	0.21	0.36	0.34	0.46	0.58	0.81
I_-/I_B (%)	2.47	3.23	2.89	5.27	6.45	9.00
$*I_{SP}$ (Sec.)	3100	3100	3170	3180	3170	2770
$I_B/NV_G^{3/2} \left(\frac{\eta_{\text{perv}}}{\text{hole}} \right)$	6.88	7.61	8.72	6.38	7.08	10.70
$**I_B/A$ (mA/cm ²)	4.74	5.66	6.57	4.88	5.03	5.03
Time Oper. (Hours)	1.5	13.5	28.5	52	76.6	145.2

* At $\eta_M = 100\%$, operational mass efficiency, 80 to 90%

** A is the open electrode area

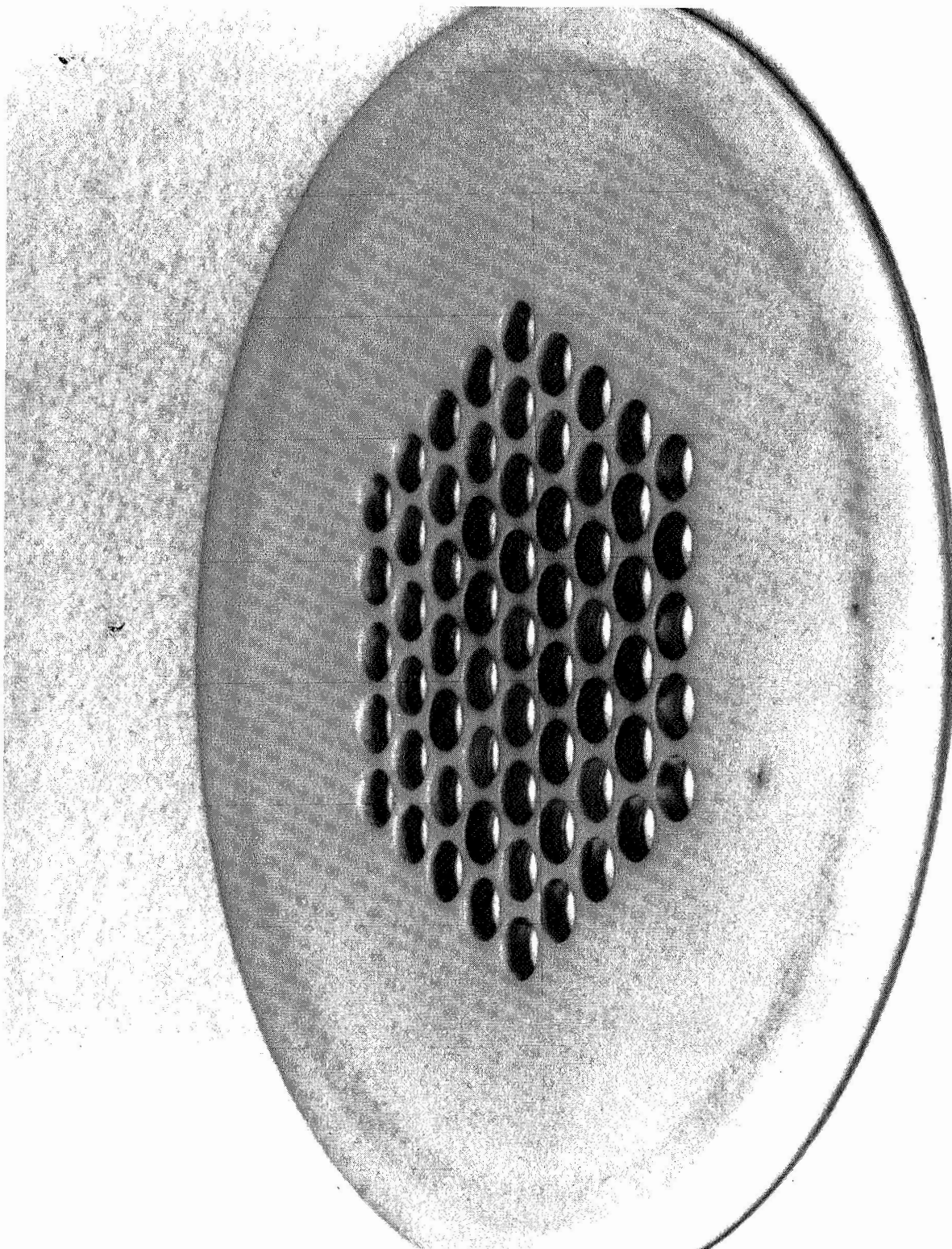


Figure 3. Brazed Alumina Electrode No. 10 after 150 Hour Test

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from the niobium accelerator electrode and alumina insulator. There were also traces of numerous other elements including the constituents of the braze material. Careful inspection of the electrode showed that the braze material had not been removed from the path of the ions. It is suspected that the coating in some apertures is partially braze material. The mass reduction after electrode operation was only 0.04 percent which is nearly the inherent balance error.

5.3 BRAZED ALUMINA ELECTRODE NO. 10 - 200 HOUR TEST

Electrode No. 10 was first operated on 5 January 1970, for 1.3 hours with drain currents starting at 1.53 percent and rising to 10 percent. The electrode was removed from the thruster and the downstream aide of the electrode was beveled. All of the niobium in the apertures was removed, however, the hard braze material remained. The electrode was operated again on 12 January 1970 and ran for 150 hours as described in subsection 5.2. Drain currents were below 4 percent for 35 hours and below 10 percent for 120 hours. The electrode was removed from the thruster and the braze material was carefully removed from the apertures.

On 4 March 1970, the electrode began its final operational test for 200 hours. Data for typical operation is given in Table VII. The sparking rate was very low throughout the test. The percentage drain currents were below 4 percent for 120 hours, but rose sharply at that time as shown on Figure 4. The mass loss during operation was 0.09 percent. Inspection of the electrode revealed that numerous cracks, visible in Figure 5, were responsible for the high drain currents. The cause of the cracking is not known. There may be a high thermal gradient from the upstream to the downstream side of the electrode which could cause stress. Thermal expansion could cause a force from the electrode mounting clamp. Fastening a thermocouple to the accelerator electrode might also weaken the alumina insulator. Long term

TABLE VII

TYPICAL OPERATIONAL DATA FOR BRAZED AL95 ELECTRODE NO. 10 - 200 HOUR TEST

Data Point No.	311	332	338	348	357	382
V_+ (V)	490	505	510	510	500	400
V_- (V)	125	125	125	104	120	64
I_B (mA)	8.50	8.00	7.74	7.99	8.02	8.40
I_- (mA)	0.20	0.20	0.23	0.27	0.89	0.815
I_-/I_B (%)	2.35	2.50	2.97	3.38	11.1	9.70
$*I_{SP}$ (Sec.)	2720	2760	2770	2770	2750	2460
$I_B/NV_G^{3/2} \left(\frac{\eta_{perv}}{hole} \right)$	9.06	8.29	7.83	8.52	8.47	13.63
$**I_B/A$ (mA/cm ²)	4.76	4.48	4.33	4.47	4.49	4.70
Time Oper. (Hours)	3	53	41	102	143	172

* At $\eta_M = 100\%$, operational mass efficiency, 80 to 90%

** A is the open electrode area

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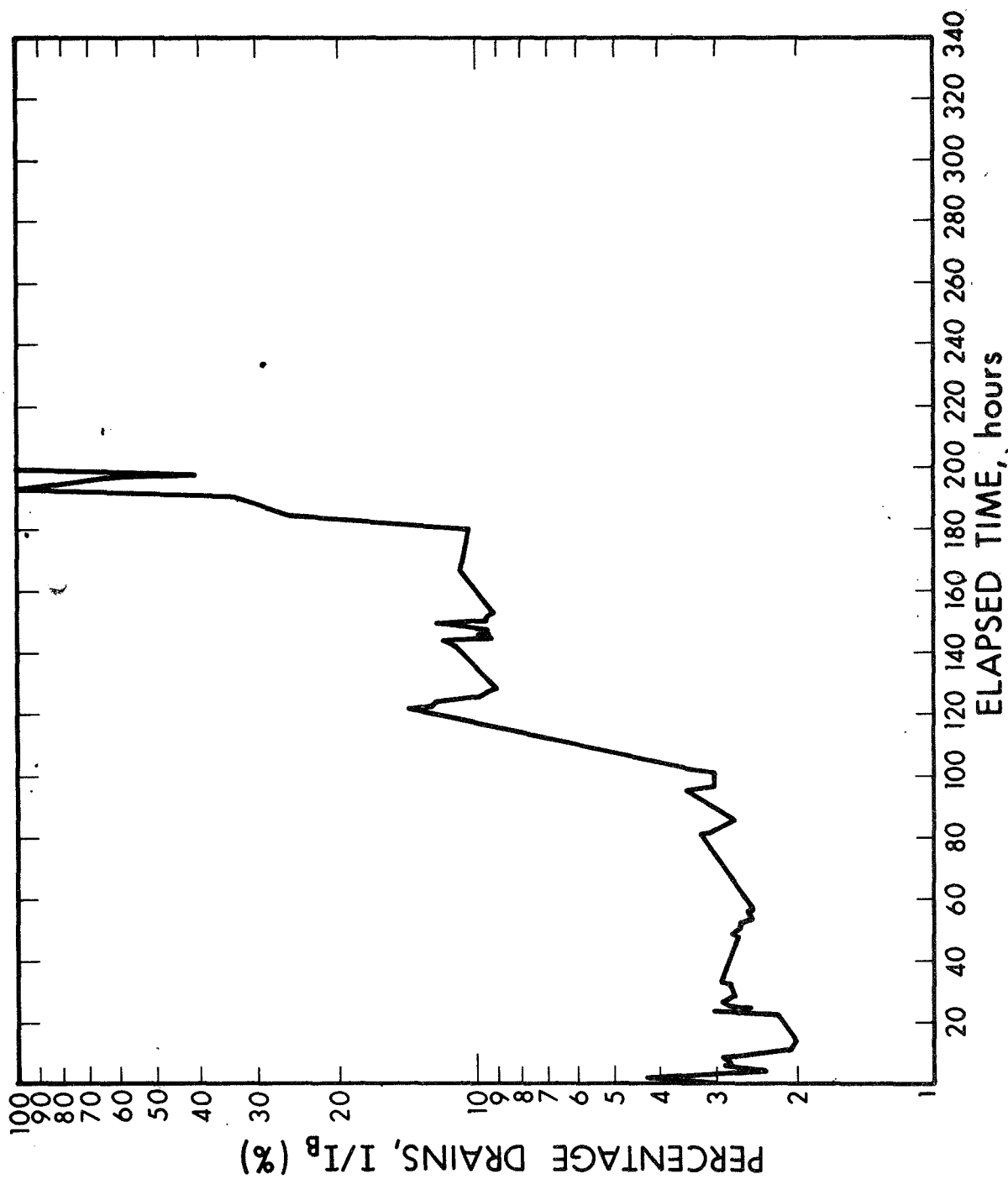
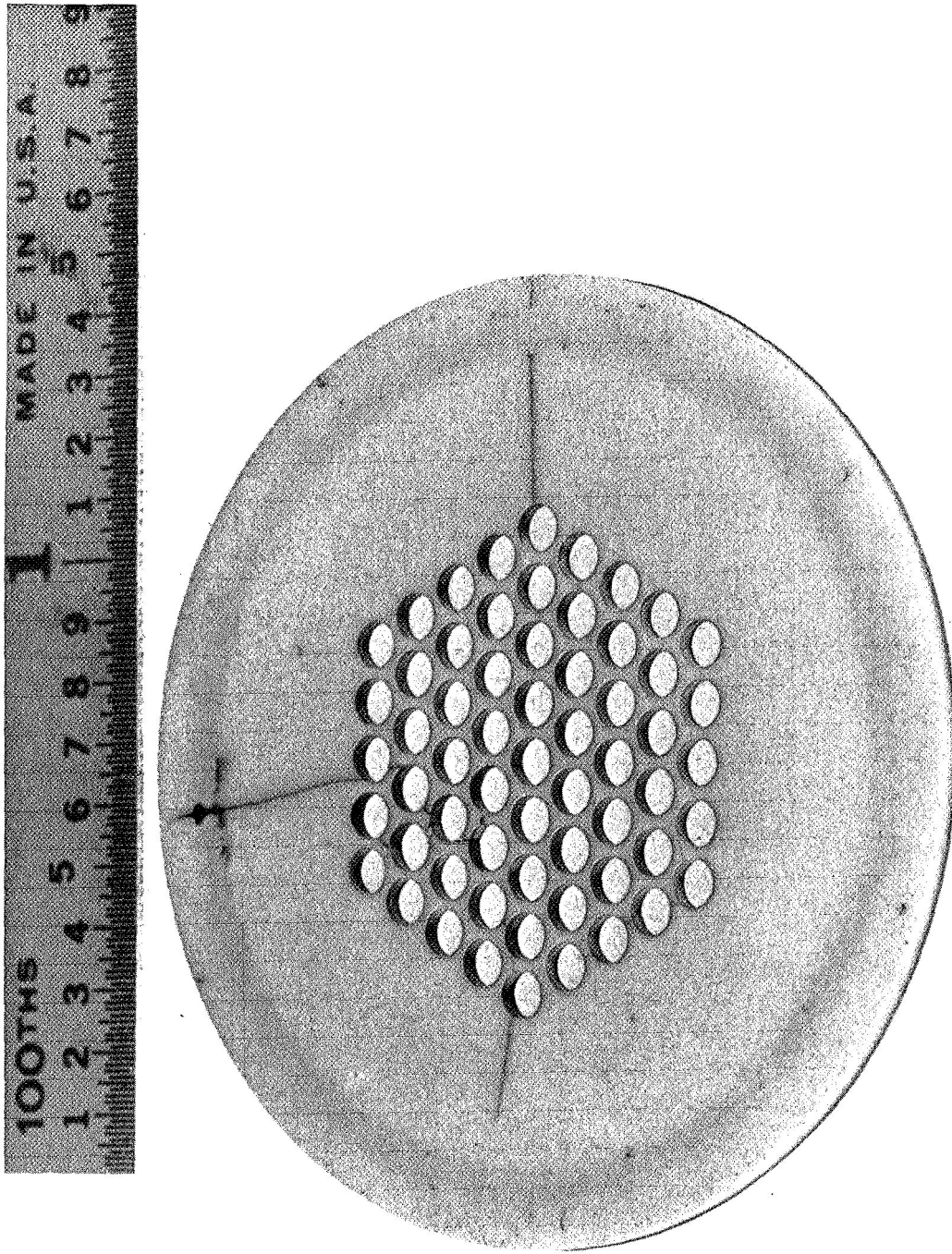


Figure 4. Percentage Drains Histogram for Electrode No. 10 after 200 Hour Test



Electrode 10 after 200 hrs

Figure 5. Brazed Alumina Electrode No. 10 after 200 Hour Test

electrical breakdown could cause crack propagation similar to "treeing". Another theory is that there are residual stresses from fabrication which help to propagate cracks with time and other forces. A new mounting technique was employed later in the program which eliminated the first three possibilities. Long term electrical breakdown is unlikely since the electric field is only 16 volts/mil. Residual stresses from fabrication can be eliminated by using different machining techniques and by heat treating.

5.4 THICK 7052 GLASS COATED ELECTRODE - 268 HOUR TEST

The thick 7052 glass coated molybdenum accelerator electrode was fabricated by T. Heslin at NASA, Goddard Space Flight Center. The glass electrode appeared bubble free with only two imperfections. They did not cause problems during testing. The glass thickness varied from up to 0.020 inch thick at the edge and center to approximately 0.005 inch thick on the webs of the peripheral holes.

The glass coating was not flat so a soft copper gasket was used between the glass surface and mounting screen. Moderate clamping sealed the joint and no further trouble was experienced. Data points for typical operation are given in Table VIII. Near the end of the test, 10^{-4} torr of argon gas was let into the vacuum chamber and the beam produced a visible glow. The beam was collimated to less than a 15° included angle. The sparking rate was low for most of the test. The percentage drain currents remained below 4 percent for 125 hours as shown in Figure 6. Failure of the electrode was more of a degradation than a catastrophic failure. The test was terminated because a web between two peripheral holes was missing, as shown in Figure 7. The web failure occurred where the glass coating was thinnest. Microscopic examination showed chipping of the glass in the apertures, cracks through the webs, ion beam erosion where cracking occurred, and remelting of

TABLE VIII

TYPICAL OPERATIONAL DATA FOR THICK 7052 GLASS COATED ELECTRODE - 268 HOUR TEST

Data Point No.	408	418	421	435	449	455
V_+ (V)	500	410	425	426	420	410
V_- (V)	80	95	90	93	230	210
I_B (mA)	7.50	8.11	7.80	8.04	8.70	11.1
I_- (mA)	0.172	0.185	0.22	0.316	0.71	2.1
I_-/I_B (%)	2.29	2.28	2.82	3.93	8.17	18.9
$*I_{SP}$ (Sec.)	2745	2490	2530	2530	2520	2490
$I_B/NV_G^{3/2} \left(\frac{\eta_{perv}}{hole} \right)$	8.84	11.7	10.9	11.15	8.62	11.7
$**I_B/A$ (mA/cm ²)	4.43	4.79	4.62	4.76	5.16	6.57
Time Oper. (Hours)	4.3	28	70	123.4	189	244

* At $\eta_M = 100\%$, operational mass efficiency, 80 to 90%

** A is the open electrode area

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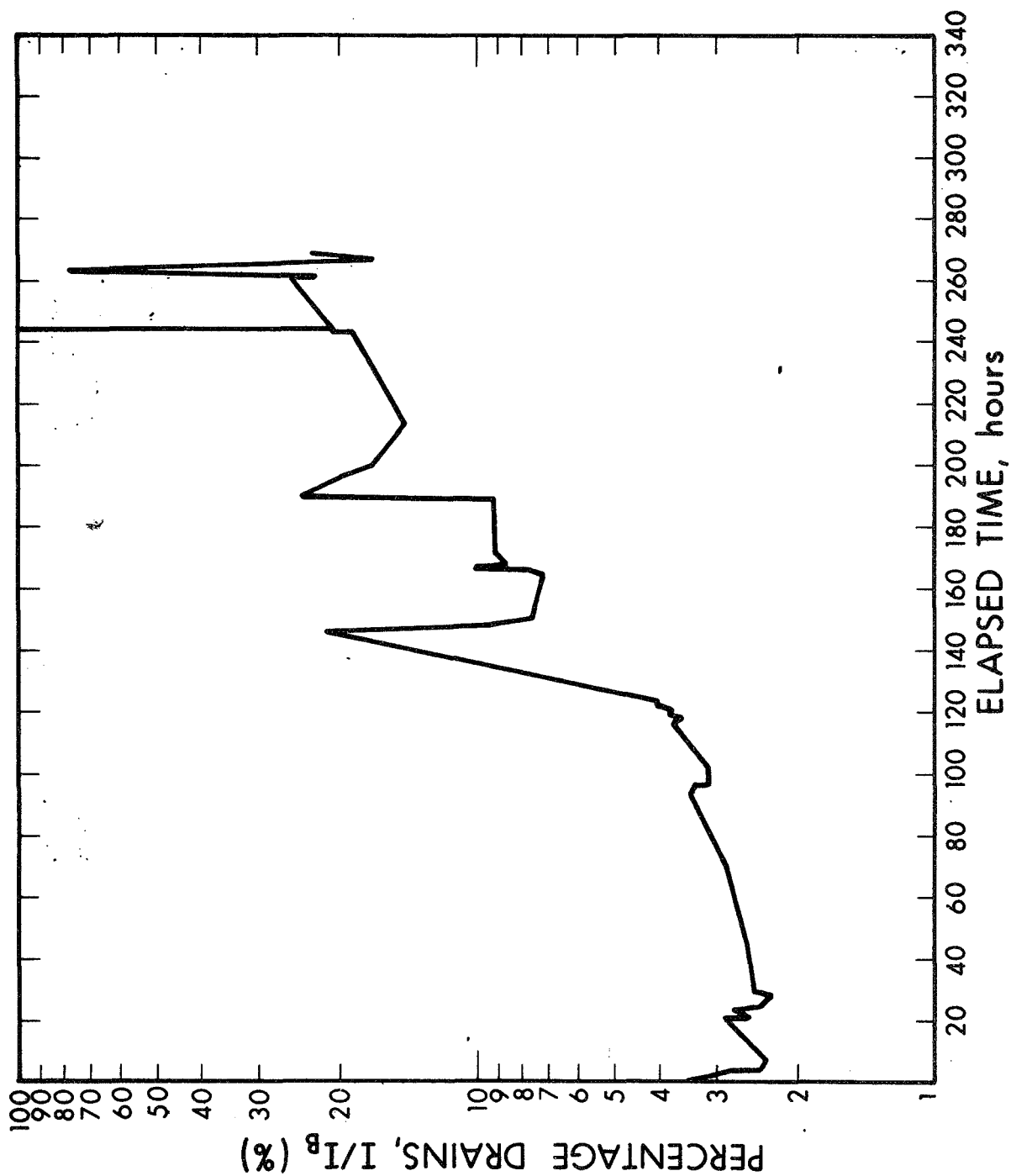


Figure 6. Percentage Drains Histogram for the Thick 7052 Glass Coated Electrode - 268 Hour Test



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Figure 7. Thick Corning 7052 Glass Coated Electrode after 268 Hour Test

glass over the cracks (possibly in that order). Some of the peripheral webs have brownish spots on them which may be due to the effects of heat and cesium on 7052 glass. All breakdown occurred where the glass coating was thinnest, i.e., on the webs of the peripheral holes. The only exception was at the copper mounting gasket. This would indicate that a thicker glass coating on the peripheral webs and a more alkali resistant glass (1723) should correct the wear out problem.

A thick 1723 glass coated accelerator electrode was fabricated by T. M. Heslin, and was operationally tested at EOS. The startup of the thruster with the glass electrode was very sparky with 60 percent drain currents. The maximum gap voltage was 596 volts with 5.3 milliamperes of beam. The test was terminated after starting the thruster twice for a total operating time of about an hour. The glass was eroded from the outside portion of the peripheral apertures. This mode of failure is indicative of the glass coating thinning at edge apertures. The glass thickness was later measured to be less than 0.001 inch at the breakdown sites. The thick 7052 glass electrode previously mentioned did not fail in this mode. The test was not of sufficient duration to determine the long term effects of cesium plasma on 1723 glass. It is felt that the thin glass at the edge of the hole array is preventing long term tests.

5.5 MOLY-MANGANESE METALIZED ALUMINA ELECTRODE NO. 15 - 212 HOUR TEST

The first metalized composite electrode, A, was fabricated by moly-manganese metalizing an 0.037-inch thick alumina disc perforated with 61 holes (type 1) of 0.076-inch diameter on 0.100-inch center-to-center spacing for a 52 percent transparency. A nickel plating was added to give a conductor thickness of 0.005 inch. The conductor extended about 0.012 inch into the apertures to effectively reduce the insulator thickness to 0.025 inch. The hole diameter insulator thickness ratio was then 3 rather than 2 as in all previous alumina niobium

composite electrodes. The thruster was operated for 60 minutes with drain currents ranging from 2 percent to 162 percent of the beam current. The test was concluded when drain currents continued to increase.

Electrode A was removed from the thruster and cleaned using water and then a dry hone. The clean electrode was then reinstalled onto the DG thruster with a dummy screen and positive mounting clamp. The electrode operated continuously for 56 minutes of which 47 minutes were completely without any high voltage arcing.

After the second test, electrode A was removed from the thruster. There was a CsOH coating on the dummy screen and a black coating in the aperture of the insulator and conductor. A shiny ring on the upstream side of the conductor in the aperture was visible due to direct ion impingement. The nickel plated moly-manganese conductor seemed to be bubbling and lifting off the insulator. The electrode was washed with water, dried by force air, and dry honed. The clean composite electrode was reinstalled on the DG thruster and operated. Drain currents were higher than the beam currents.

The moly-manganese electrode was removed from the vacuum chamber and examined under a microscope before any cleaning. Numerous cracks in the insulator accounted for the high drain currents. The cracks were parallel which indicated the alumina was cracked in tension during cleaning with the dry hone. Future cleanings with the hone used a lower air pressure and a fixture to uniformly support the electrode and keep it flat.

The conductor was found to be lifting off the alumina. This was due to the difference in coefficients of thermal expansion and differences in bond strengths. The nickel overplate expands at a high rate compared with molybdenum and alumina. This causes stress which tends to

blister the nickel. The bond between the molybdenum and alumina is a brittle oxide bond whereas the bond between the nickel and molybdenum is relatively strong. The force applied by the expanding nickel caused the alumina to moly-manganese bond to break, separating the conductor and insulator. This did not occur where the plating had extended into the apertures.

A second moly-manganese metalized electrode, designated No. 15, was fabricated, but was not plated with nickel. Electrode No. 15 was operated without removing the metalizing which partially coated the inside of the holes. The percentage drains were below 5 percent for about 50 hours of the 56 hours operational test. After extinguishing the arc, there were residual drain currents. These were gone 2 minutes after shutdown. The residual drains may indicate that cesium vapor was condensing on the electrode. Inspection of the electrode showed erosion of the moly-manganese metalizing in the holes and a conductive coating (not cesium) in the holes. This coating is probably moly-manganese which has been dislodged by direct exposure to the ion beam.

The MoMn electrode was then cleaned with a dry hone and beveled on the downstream side. This eliminated all conductive material in the path of the ion beam. The thruster was operationally tested with MoMn electrode No. 15 for a second time. The enlarged holes in the MoMn accelerator grid required high gap voltages for the same beam current and therefore was operated at relatively low perveance. The test ran for 212 hours with low percentage drains for 172 hours as shown in Figure 8. Typical operating data, given in Table IX, shows that the perveance was reduced from previous tests. This composite electrode had the lowest drain currents of any tested. This is attributed to the very thin accelerator electrode and to the downstream beveling. A post-test inspection showed that the high drain currents resulted from a thin conductive coating in the apertures.

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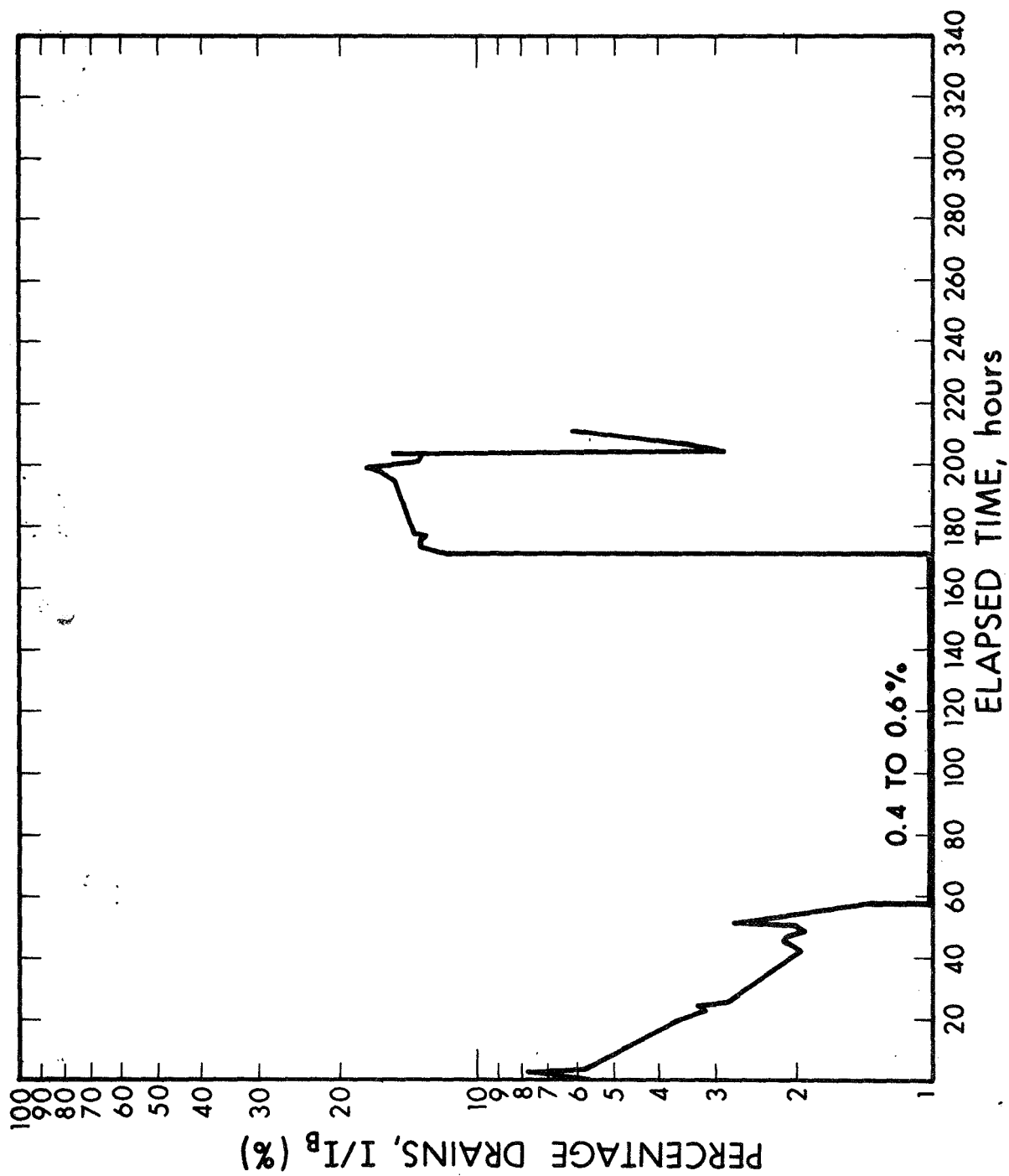


Figure 8. Percentage Drains Histogram for MoMn Electrode No. 15 after 212 Hour Test

TABLE IX

TYPICAL OPERATIONAL DATA FOR MOLY-MANGANESE ELECTRODE NO. 15 - 212 HOUR TEST

Data Point No.	509	519	531	584	593	620
V_+ (V)	895	899	870	875	873	948
V_- (V)	252	253	251	253	250	212
I_B (mA)	4.40	4.315	5.90	6.14	6.20	8.195
I_- (mA)	0.25	0.085	0.032	0.026	0.044	0.235
I_-/I_B (%)	5.68	1.97	0.54	0.42	0.71	2.87
$*I_{SP}$ (Sec.)	3680	3680	3620	3630	3625	3780
$I_B/NV_G^{3/2} \left(\frac{\eta_{\text{perv}}}{\text{hole}} \right)$	1.47	1.44	2.57	2.67	2.68	2.71
$**I_B/A$ (mA/cm ²)	2.46	2.43	3.30	3.43	3.47	4.58
Time Oper. (Hours)	2.5	42	61	124	155	206

* At $\eta_M = 100\%$, operational mass efficiency, 80 to 90%

** A is the open electrode area

The coating was cleaned from the electrode using the dry hone. The upstream and downstream bevels were cleaned with the diamond counter-sink. The thruster was restarted and operated for 5.25 hours with high drain currents. The electrode was withdrawn from the thruster and inspected for cracks. None were found. The electrode was cleaned with the dry hone and restarted. It operated for 40 hours before a power failure caused an emergency shutdown of the vacuum system. The next morning the test was continued for an additional 26.5 hours. The drain currents were higher than 10 percent throughout the 66.5 hours of testing. External examination of the electrode showed that the drains were caused by cracks in the electrode. The test was terminated.

5.6 FLANGED LUCALOX ELECTRODE NO. 25 - 104 HOUR TEST

Composite Electrode No. 25 was a 0.005-inch thick niobium electrode brazed to a 0.037-inch thick Lucalox insulator. On the periphery of the upstream insulator a mounting flange was brazed as shown in Figure 9. A convolution in the 0.010-inch thick mounting flange was intended to absorb stresses due to improper mounting and thermal gradients. This mounting configuration meets the requirements of a flight type electrode mount. The relatively small heat dissipating area insured a uniform temperature throughout the composite electrode.

The thruster startup was very smooth and control was good throughout the test. During the first test the drain currents reduced steadily for 6.25 hours and then increased steadily for the next 14 hours when the test was terminated. This test ran as expected since it was known that the hard braze material was still in the holes. The electrode was removed from the thruster and cleaned with a 12 flute ball reamer and the dry hone.

The thruster was restarted smoothly and operated for 104 hours. The drains decreased for the first 8 hours and then began to increase

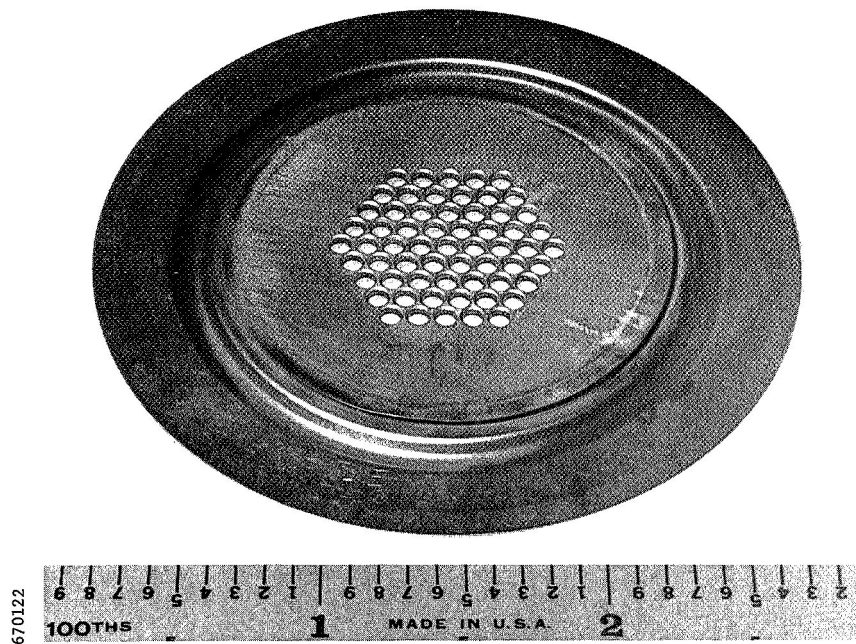


Figure 9. Flanged Lucalox Electrode No. 25 after
104 Hour Test

slowly for the remaining 96 hours. The test was terminated with 7.8 percent drain currents as shown in the percentage drains histogram, Figure 10. Typical operational data is given in Table X. The pervance is quite acceptable even though a relatively low beam level was selected for operation. The operational characteristics indicated that some of the braze material was probably left in the holes and was building up a coating in those holes. Removal and inspection proved the theory correct.

5.7 FLANGED 7052 GLASS COATED ELECTRODE - 320 HOUR TEST

The flanged 7052 glass coated molybdenum accelerator electrode was designed to test the center portion of the glass coating without worrying about edge effects. The thin glass around the periphery of previous glass coated grids has always limited the duration of operational tests. The glass coating at the center of the electrode was measured to be 0.015-inch thick. The mounting flange enabled flight type mounting on the thruster and provided a shadow shield for the adhesive connecting the flange to the glass. This mounting procedure also thermally isolated the electrode allowing the temperature to be more uniform. An additional shadow shield was attached to the accelerator grid to prevent surface breakdown of the adhesive on the downstream side. The 0.75-inch diameter hole in the center of the mounting flange allowed the plasma to directly bombard only the 61 holes of a type 1 configuration. The Ceramabond cement filled in two rows of the peripheral holes.

The thruster started smoothly with 6.17 percent drain currents. In 15 minutes the drains had dropped to 2.63 percent. During the next 30 minutes a control system malfunction caused the arc chamber to have too much cesium resulting in a very high arc current for a few minutes. After the automatic control of the thruster recovered, the percentage

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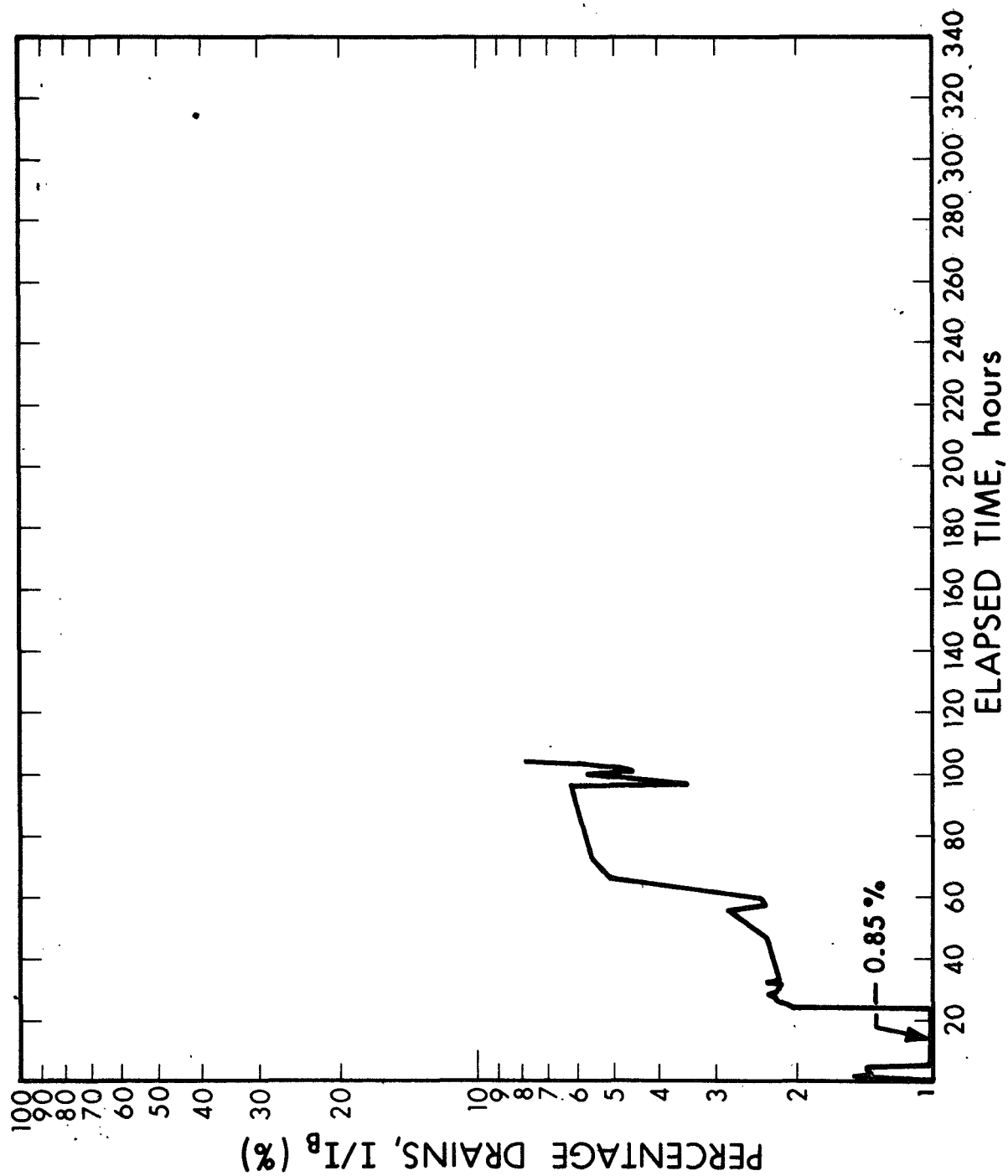


Figure 10. Percentage Drains Histogram for the Flanged Lucalox Electrode No. 25 after 104 Hour Test

TABLE X

TYPICAL OPERATIONAL DATA FOR FLANGED LUCALOX ELECTRODE NO. 25 - 104 HOUR TEST

Data Point No.	715	721	730	736	739	747
V_+ (V)	532	525	526	525	510	488
V_- (V)	224	224	224	202	205	203
I_B (mA)	8.81	9.55	9.48	9.46	9.65	14.6
I_- (mA)	0.120	0.080	0.201	0.313	0.600	0.660
I_-/I_B (%)	1.37	0.84	2.12	3.32	6.22	4.53
$*I_{SP}$ (Sec.)	2830	2815	2816	2815	2775	2720
$I_B/NV_G^{3/2} \left(\frac{\eta_{\text{perv}}}{\text{hole}} \right)$	6.92	7.60	7.56	7.88	8.19	13.21
$**I_B/A$ (mA/cm ²)	4.93	5.33	5.30	5.28	5.39	8.17
Time Oper. (Hours)	2	8	31	58.6	72.4	101

* At $\eta_M = 100\%$, operational mass efficiency, 80 to 90%

** A is the open electrode area

drains were 13.5 percent and dropping. The percentage drain currents continued to drop for the next 190 hours as seen in Figure 11. At 190 hours an upward trend started for the percentage drains which avalanched at 320 hours. Table XI shows that the thruster operational parameters were very consistent throughout the test, except for the control runaway during the first hour. It is not possible to assess what damage, if any, was done to the electrode during the control runaway. Such a runaway can be caused by malfunctioning accelerator electrodes or by several other components in the ion engine system. The possibility of a control runaway was eliminated in subsequent tests by controlling the vaporizer current with the positive high voltage supply current (I_+) rather than the beam current (I_B).

The test was officially terminated when the thruster could no longer be operated with the same parameters. However, the thruster was operated for an additional 18 hours with a reduced beam level of 3 milliamperes. It was hoped that the high drain currents were due to a temporary condition, but conditions did not improve, so the test was stopped.

The electrode was then disassembled for post-run evaluation. The upstream and downstream sides of the glass coated electrode are shown in Figures 12 and 13, respectively. These pictures were taken immediately after removal from the vacuum chamber. The cesium hydroxide coating visible as splotches on the flat metal surfaces is due to thruster shutdown and does not affect thruster operation. The Ceramabond cement filling in the apertures appeared to be unharmed in any way.

A microscopic examination of the electrode after operation revealed the following observations:

- a. The high drain currents were primarily due to a few eroded holes at the edge of the beam. This is visible in Figures 12 and 13. On the upstream side, one web has no glass and one web has the glass severely eroded.

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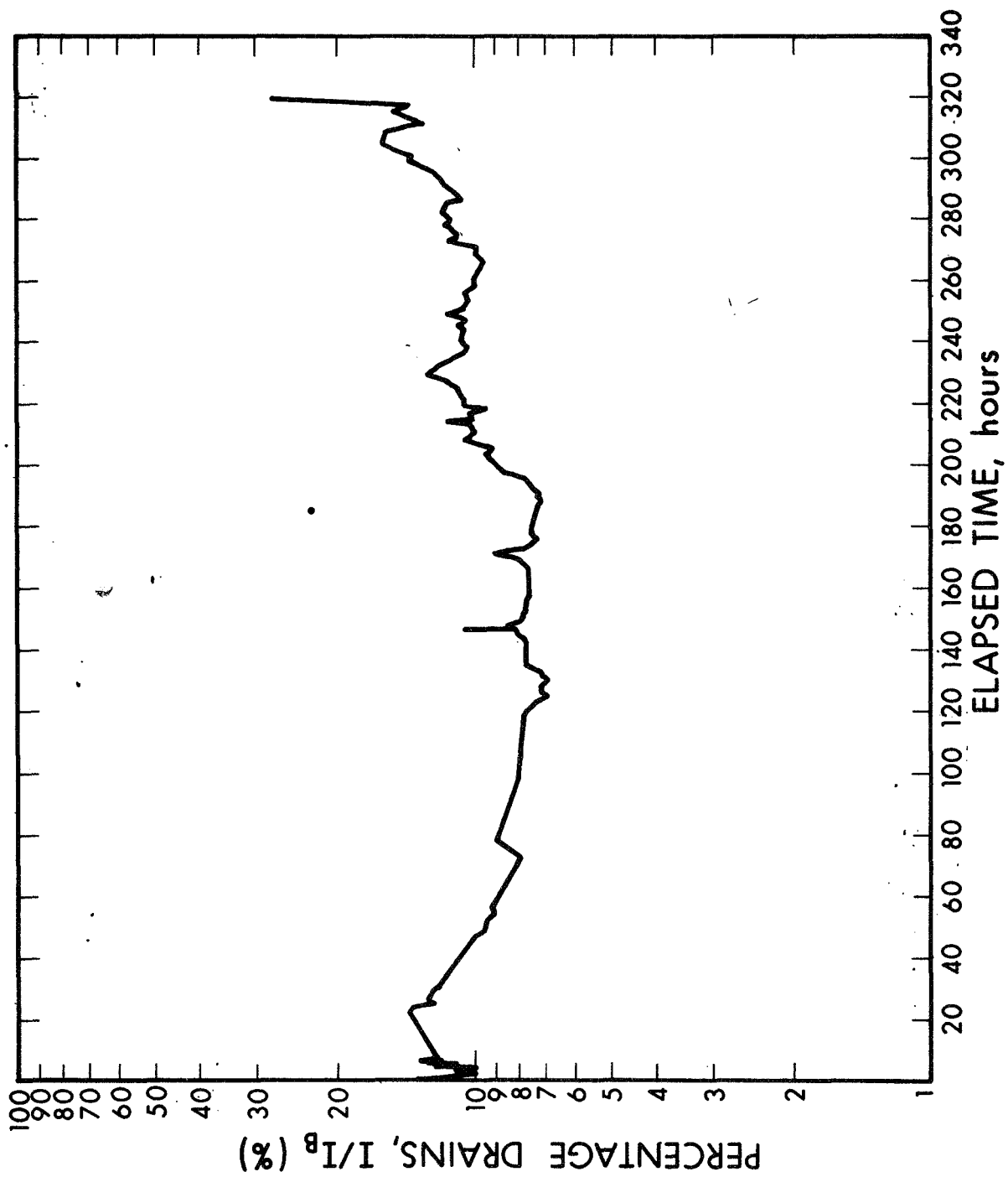


Figure 11. Percentage Drains Histogram for the Flanged 7052 Glass Coated Electrode after 320 Hour Test

TABLE XI

TYPICAL OPERATIONAL DATA FOR FLANGED 7052 GLASS COATED ELECTRODE - 320 HOUR TEST

Data Point No.	754	759	791	817	855	884
V_+ (V)	521	515	517	514	512	519
V_- (V)	205	202	203	203	201	203
I_B (mA)	5.1	6.50	6.07	6.05	6.00	6.10
I_- (mA)	0.135	0.635	0.470	0.442	0.630	0.785
I_-/I_B (%)	2.63	9.75	7.77	7.32	10.5	12.9
$*I_{SP}$ (Sec.)	2810	2785	2790	2780	2775	2800
$I_B/NV_G^{3/2} \left(\frac{\eta_{perv}}{hole} \right)$	4.28	5.54	5.13	5.16	5.18	4.96
$**I_B/A$ (mA/cm ²)	2.83	3.62	3.37	3.36	3.33	3.38
Time Oper. (Hours)	0.25	2.2	118.7	176	247	311

* At $\eta_M = 100\%$, operational mass efficiency, 80 to 90%

** A is the open electrode area

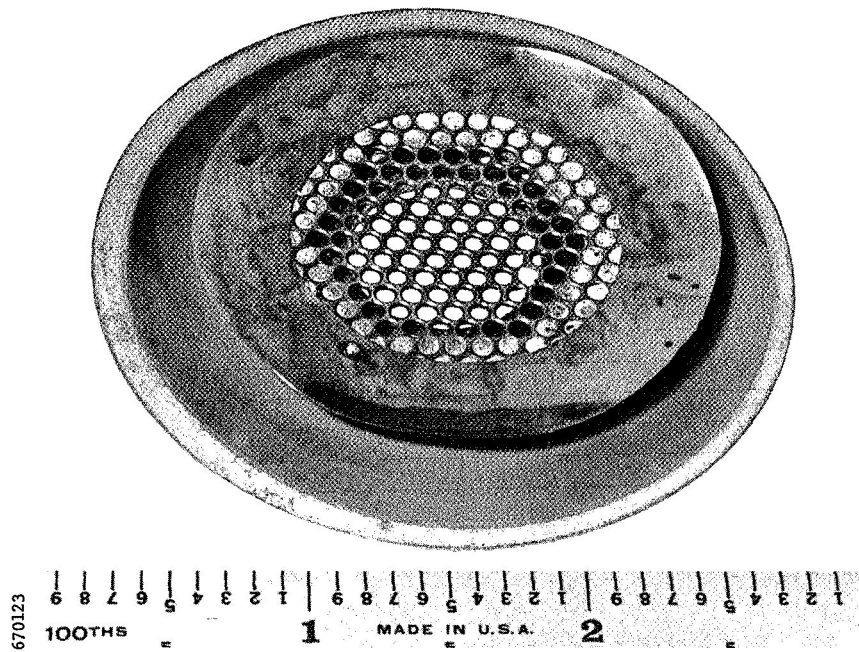


Figure 12. Flanged 7052 Glass Coated Electrode after
320 Hour Test (Downstream Side)

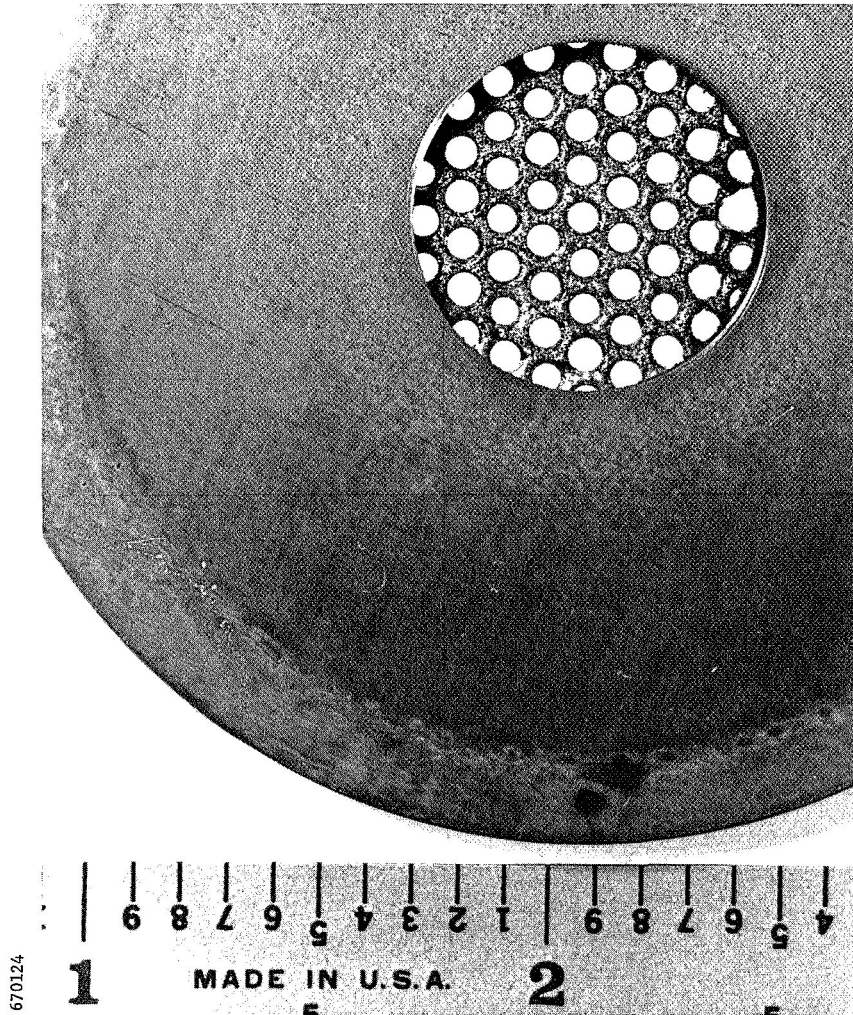


Figure 13. Flanged 7052 Glass Coated Electrode after 320 Hour Test (Upstream Side)

- b. The inside mounting screen has a deposit near the eroded hole only. The deposit appears to be burnt ceramic and glass.
- c. Several of the bubbles, which were accidentally produced during glass coating, burst during operation. Some holes look burned as if an arc passed through them. The burned bubble holes appeared all over the electrode with the majority near the edge of the glass coating.
- d. The glass around the eroded hole is amber colored.
- e. The glass in the area exposed to the cesium plasma has a gold colored deposit between the 7052 glass and the molybdenum accelerator grid (or between layers of glass). The gold color is not uniform and looks like pure cesium. This is characteristic of alkali attack on glass.
- f. There is a white powdery substance between the mounting flange and the glass coating.
- g. The glass surface was unharmed and clean except where bubbles burst.

The two main problems with the electrode seem to be bubbles in the final glass coating and alkali attack of the 7052 glass. Bubble-free 1723 glass coatings were subsequently produced by T. M. Heslin at the Advanced Materials Branch of NASA, Goddard Space Flight Center. The lack of bubbles eliminated the first problem. Corning code 1723 glass, resistant to alkali attack, was adopted to eliminate the second problem.

5.8 GLASS COATED BRAZED ALUMINA ELECTRODE NO. 30 - 165 HOUR TEST

Composite electrode No. 30 was fabricated by perforating a 0.037-inch thick AL995 alumina disc with 61 holes, 0.076-inch in diameter on 0.100-inch centers. This alumina insulator was then brazed to a matching niobium grid 0.005-inch thick. At this stage, the composite grid was called electrode No. 6 and was operated for 1.3 hours on 4 November 1969. The percentage drains during the test were very high and microcracks were suspected.

Since that early test, methods to reduce the possibility of cracking were established. The primary mode of degradation of brazed alumina electrodes became a conductive black coating in the apertures. This black coating is thought to be trapped by the materials surface porosity. GSFC developed a technique for applying a 0.002-inch thick coating of Corning code 1723 glass to the alumina insulator, thus sealing the surface. Electrode No. 6 was sent to GSFC and the alumina was glass coated without significantly changing the aperture, size or shape. Unfortunately, thermal gradients during the glassing produced cracks which were glass covered. The now glass-coated, brazed alumina electrode, No. 30, was returned to EOS for operational testing in January, 1971.

Upon return to EOS, electrode No. 30 was cemented to a convoluted niobium mounting flange using Ceramabond 503 and fired at 450°C for 1 hour in dry argon. A stainless steel foil shadow shield was spot welded to the downstream niobium accelerator electrode. Electrode No. 30 was mounted on the 1.5-inch thruster with a 5-pound feed system.

A newly derived startup procedure was followed exactly for a very smooth startup. The beam was brought up to 6.25 milliamperes, with a percentage drain of 3.7 percent. V_+ was 500 volts and V_- was 250 volts. After 18.5 hours of operation, the percentage drains drifted up to 11.7 percent. The V_+ was raised to 600 volts with V_- at 200 volts to improve focusing after 48 hours. The beam reference was lowered to 4.6 milliamperes with 20.6 percent percentage drains. The parameters were kept in this range for the remainder of the 165 hours of operation. The percentage drains seemed to rise exponentially to a terminal value of 58.8 percent. The test was terminated to determine the cause of the high percentage drains.

The high drain currents were caused by cracks in the alumina which had been covered by glass before the test started. The thin layer of glass

was not sufficient by itself to stand off the 835-volt maximum gap potential difference. There was no black conductive coating in the apertures as experienced by previously brazed alumina electrodes. The Ceramabond had sufficient strength, but was discolored and more conductive, possibly from back-sputtering. The 1723 glass is still present on the alumina except where dielectric breakdowns occurred through the cracked alumina.

This test was very encouraging and appeared to indicate that the development was progressing. It is believed that a glassed-alumina electrode has the potential for solving the lifetime problems experienced on this program. The two problems mentioned here, cracked alumina and Ceramabond bonding of flange to electrode, have been avoided in the most recent fabrication effort by Mr. Heslin at GSFC. It is anticipated that the electrode, No. 37, will give excellent performance.

SECTION 6

CONCLUSION

The primary objective of this program was to demonstrate the feasibility of incorporating composite accelerator grids on cesium electron bombardment ion thrusters. This objective was met by demonstrating operation at low specific impulse, from 1800 to 3500 seconds with three types of composite grids. However, as with mercury bombardment thrusters, development effort is still needed to extend lifetime to useful lengths. The goal of 1000 hours operation was not achieved. Several trial tests were made, but none extended significantly beyond a third of the goal. It is clear that more investigation is needed to identify and understand the limitations of electrode life. Nevertheless, much progress was made in the use of composite grids.

High transparency electrodes consisting of niobium brazed to alumina and molybdenum-manganese metalized alumina were brought from first simple attempts to functioning, effective ion extraction systems. Corning 7052 and 1723 glass coating techniques were developed by T. M. Heslin and A. G. Eubanks at NASA/GSFC in a parallel effort and these electrodes were operated successfully.

The major problem experienced during the program was electrical breakdown of the electrodes after extended testing. Operation would be ideal for as long as 170 hours before decay would slowly set in. The cause of the breakdown appeared to be a conductive coating forming in the apertures of the alumina electrodes. The source of the coating was not positively identified during the program. Sputtered material from the chamber walls or from ion impingement on the accelerator conductive surface is the most likely candidate.

In hopes of eliminating the coating problem which appeared to be encouraged by the porous nature of the alumina, efforts were turned to glass coated molybdenum grids. The fused surface of the glass resisted the coating, but thickness control fabrication, particularly near the edges was a continuing problem. Grids would operate satisfactorily for a while, then break down.

The next logical step is hybrid composite electrodes composed of glass coated alumina with appropriate conductor, shadow shield, and mounting flange. By making use of the non-coating properties of glass and the electrical isolation and geometric control of alumina, an attractive solution seems available. Such an electrode has been fabricated through a joint effort of EOS and GSFC, but has not been tested at this writing.

The lifetime problem has been elusive, but a solution appears to be nearly at hand. Continued investigation could well bring the advantages of composite electrodes to useful application on flight hardware.

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